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DEVELOPMENT OF EMISSION FACTORS FOR FUGITIVE DUST SOURCES

Chatten Cowherd, Jr., et al

Midwest Research Institute

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For each source type, emissions are related to meteorological and source parameters, including properties of the emitting surface and characteristics of the vehicle or implement which causes the emission. This information is used to derive correction factors which appropriately adjust basic emission factors to reflect regional differences in climate and surface properties.

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PREFACE

This report was prepared for EPA's Office of Air Quality Planning and Standards, under Contract No. 68-02-0619. Mr. David Anderson and Mr. Charles Mann served as EPA project officers. The work was performed in the Physical Sciences Division of Midwest Research Institute under the supervision of Dr. Larry Shannon, Head, Environmental Systems Section.

Dr. Chatten Cowherd, Jr., Principal Investigator, was the principal author of this report. He was assisted by Mr. Kenneth Axetell, Jr., and Mr. George Jutze of PEDCo-Environmental (Subcontractor), who drafted the first part of Chapter 6, Chapter 7, Appendix A and Appendix B. Other MRI staff members who contributed to the program included Miss Christine Guenther and Mr. Francis Bennett.

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ABSTRACT

This report presents the results of an extensive field testing program to develop emission factors for certain common sources of fugitive dust. The source categories that have been investigated are: agricultural tilling, unpaved roads and air strips, heavy construction activities, and aggregate storage piles. Characterization and quantification of emissions from these sources are necessary to the development of effective control strategies so that the national air quality standards for total suspended particulates may be achieved.

Because little reliable emissions data existed for these sources prior to this study, an extensive program of field sampling was required to generate the data which would provide the basis for emission factor determination. To this end, fugitive dust sampling techniques and associated data reduction schemes were developed to quantify emissions from moving and stationary dust sources. The basic measurements consisted of isokinetic dust exposure profiles with specially designed sampling equipment, dust concentrations with conventional high-volume samplers, particle size classification with high-volume cascade impactors, deposition profiles and dust transport by saltation. A description of the measurement techniques and summaries of calculated test results are presented.

For each source type, emissions are related to meteorological and source parameters, including properties of the emitting surface and characteristics of the vehicle or implement which causes the emission. This information is used to derive correction factors which appropriately adjust basic emission factors to reflect regional differences in climate and surface properties.

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EXECUTIVE SUMMARY

This report presents the results of an extensive field testing program which was conducted to determine emission factors for four categories of fugitive dust sources:

1. Unpaved roads and airstrips
2. Agricultural tilling
3. Construction sites
4. Aggregate storage piles

The testing was necessitated by the lack of reliable data on the characteristics of these sources.

Special dust sampling techniques and associated data reduction schemes were developed to quantify emissions from moving and stationary fugitive dust sources. The two basic plume sampling techniques were isokinetic exposure profiling and conventional high-volume sampling with wind direction activators. The effective dust cut-off diameter for the standard high-volume sampler was found to be about 30 μm.

During each field test, source activity and meteorological conditions were continuously monitored. In addition, samples of the emitting surface material were collected for laboratory analysis.

Test sites were concentrated in the dust bowl area of the Great Plains. However, emissions from aggregate storage piles were tested in the Cincinnati and Kansas City areas.

For each source type, the observed relationship between emission rate and source activity was used to derive a basic emission factor. In addition, test data were analyzed to determine the dependence of the emission rate on properties of the emitting surfaces and characteristics of the vehicle or implement which caused the emissions.

The corrected emission factors which were developed for each source category and the associated particle size breakdowns are presented in the following paragraphs.

UNPAVED ROADS

The equation for estimating the total amount of road dust emissions with drift potential greater than 25 ft, i.e., particles smaller than 100 μm in diameter, is as follows:

$$e_{(roads)} = 0.81\ s\ (S/30)$$

where e = emission factor (pounds per vehicle-mile)
s = silt content of road surface material (percent)
S = average vehicle speed (miles per hour)

The precision of this equation in predicting the results of the emission tests of unpaved roads is ± 10%.

The aggregate silt* content (i.e., particles smaller than 75 μm in diameter) of the road surface is determined by measuring the amount of loose (dry) surface dust which passes a 200 mesh screen. The silt content of gravel roads is approximately 12%.

The above equation applies to "dry" days. Emissions are assumed to be negligible on days with rainfall exceeding 0.01 in.

The test results indicate that, on the average, dust emissions from unpaved roads have the following particle size characteristics:

Particle Diameter	Weight Percent
< 2 μm	25
2 μm - 30 μm	35
30 μm - 100 μm	40

AGRICULTURAL TILLING

The equation for estimating the total amount of tillage dust emissions with drift potential greater than 25 ft, i.e., particles smaller than 75 μm in diameter, is as follows:

---

* As defined by American Association of State Highway Officials.

$$e(\text{tilling}) = \frac{1.4\ s\ (S/5.5)}{(PE/50)^2}$$

where e = emission factor (pounds per acre)
s = silt content of surface soil (percent)
S = implement speed (miles per hour)
PE = Thornthwaite's precipitation-evaporation index (corrected for irrigation, if any)

The precision of this equation in predicting the results of the emission tests of agricultural tilling is ± 15%.

The soil silt* content (i.e., particles between 50 µm and 2 µm in diameter) may be determined by the Buoyocous hydrometer method. Surface soil samples should be extracted with a plugging device to a depth of 4 in.

The test results indicate that, on the average, dust emissions from agricultural tilling have the following particle size characteristics:

Particle Diameter	Weight Percent
< 2 µm	35
2 µm - 30 µm	45
> 30 µm	20

AGGREGATE STORAGE PILES

The corrected emission factor for estimating the total amount of dust emissions with drift potential greater than 1,000 ft, i.e., particles smaller than 30 µ in diameter, is given by the following expression:

$$e(\text{aggregate}) = \frac{0.33}{(PE/100)^2}$$

where e = emission factor (pounds per ton placed in storage)
PE = Thornthwaite's precipitation-evaporation index

Total dust emissions from aggregate storage piles can be divided into the contributions of several distinct source activities which occur within the storage cycle:

---

* As defined by U.S. Department of Agriculture.

- Loading of aggregate onto storage piles (12%)
- Equipment traffic in storage area (40%)
- Wind erosion (33%)
- Loadout of aggregate for shipment (15%)

The numbers in parentheses are the relative contributions of each activity to the total emissions.

CONSTRUCTION SITES

The emission factor for medium-type construction activities (e.g., townhouses, shopping center) averaged about 1.2 tons/acre/month. However, because of the use of water for dust control and interferences from other dust sources in the vicinity of the test sites, correlations between emission rate and potential correction parameters could not be established. There was strong evidence that the level of activity could change emissions by a factor of two or more.

The probable correction parameters for construction emissions are (1) soil silt content and (2) surface moisture and level of activity. The value reported above is thought to be fairly representative of uncontrolled emissions in areas less arid (PE ~ 50) than the Arizona-Nevada test sites, but having a similar soil silt content (~ 30%). Approximately 40% of the dust emissions are smaller than 3 μm.

CHAPTER 1

INTRODUCTION

This report presents the results of a program conducted by Midwest Research Institute to develop emission factors for estimating atmospheric emissions from certain common sources of fugitive dust.* The source categories studied were:

- Unpaved roads and airstrips
- Agricultural tilling
- Construction sites
- Aggregate storage sites

In this chapter, the background of the fugitive dust problem is reviewed, and the objectives of the investigative program are stated.

BACKGROUND

Natural dust, commonly termed "dust rise by wind," is a major source of global aerosol, accounting for as much as 20% of the total yearly production.1/ Recent studies have demonstrated that fine particles of soil and minerals drift for thousands of miles on high altitude wind currents.2,3/

On a regional scale, sources of natural dust have been associated primarily with the background particulate matter in the ambient air. The occurrence of high background dust loadings during periods of dry, windy weather has supported the widely held contention that the generation of natural dust is an uncontrollable climatic phenomenon. Except for major wind erosion damage to croplands, the effects of natural dust emissions have often been viewed as relatively inconsequential.

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* Fugitive emissions are defined as pollutant emissions which are not confined in process streams.

In recent years, however, with the development of the national effort to abate air pollution, the public has become more discerning about the differences between a purely natural dust generation process and the generation of "natural" dust resulting from the anthropogenic disturbance of a surface exposed to the air environment. For example, when the land is stripped of vegetation in preparation for a construction project, the enhanced vulnerability to wind erosion is no longer viewed as a natural phenomenon. Likewise the generation of soil and rock dust by vehicular traffic on an unpaved road is recognized as a man-made source of air pollution.

Nevertheless, the problems of localized fallout of atmospheric dust in the vicinity of common fugitive dust sources still draw markedly different reaction from different segments of the population. In rural areas the dust fallout from unpaved roads and agricultural tilling is normally accepted by local residents as a nuisance which can be tolerated. However, in the larger population centers, dust fallout from mineral mining, processing and storage operations is often decried as an intolerable nuisance and a potential health hazard.

Recently, the development of State Implementation Plans to achieve the national ambient air quality standards for suspended particulates, has revealed that fugitive dust sources (including strictly natural sources) in many areas of the country, both urban and rural, may have a much more substantial impact than once thought. In addition to large dust particles which settle out near the source and cause the nuisance problem, fine particles are also emitted and dispersed over much greater distances from the source. Although common sources of fugitive dust generally have not been regarded as serious air pollution problems, the cumulative effect of widely scattered emissions in many areas has been suggested as a major cause of noncompliance with air quality standards.

For the source categories treated in this report, there are two basic mechanisms of dust generation by disturbance of exposed surface material:

1. Pulverization and abrasion of surface material by application of force through implements (wheels, blades, etc.)
2. Entrainment of dust particles by the action of turbulent air currents.

The characteristics of dust generation for each source type will be discussed briefly in the following paragraphs.

Unpaved Roads and Air Strips

Unpaved roads are the most common transportation surface in the rural areas of the country. Dust plumes trailing behind vehicles are a common sight in these areas.

When a vehicle travels over an unpaved road, the forces of the wheels on the road surface cause pulverization of surface material. Particles are lifted and dropped from the rolling wheels and the road surface is exposed to strong air currents in turbulent shear with the surface. The turbulent wake behind the vehicle continues to act on the road surface after the vehicle has passed.

Unpaved airstrips are also common to the rural areas of the country. Emissions from unpaved airstrips are caused almost entirely by the turbulent wake generated by the propulsion systems.

Agricultural Tilling

The two universal objectives of agricultural tilling are the creation of the desired soil structure to be used as the crop seedbed and the eradication of weeds. A desirable soil structure is one in which large pores extend from the surface to the water table or drains; this structure helps to provide the right proportion of air and water for plant roots to absorb nutrients from the soil. Plowing, the most common method of tillage, consists of some form of cutting loose, granulating, and inverting the soil and turning under the organic litter. Sweeps or undercutters which loosen the soil and cut off the weeds but leave the surface trash in place, have recently become more popular for tilling in dryland farming areas.

During a tilling operation, dust particles from the loosening and pulverization of the soil are injected into the atmosphere as the soil is dropped to the surface. Dust emissions are greatest when the soil is dry and during final seedbed preparation.

Aggregate Storage Piles

An inherent part of the operation of plants that utilize minerals in aggregate form is the maintenance of outdoor storage piles. Storage piles are usually left uncovered, partially because of the necessity for frequent transfer of material into or out of storage.

Dust emissions occur at several points in the storage cycle--during loading of material onto the pile, whenever the pile is acted on by strong wind currents, and during loadout of material from the pile. The truck and loading equipment traffic in the storage pile area is also a substantial source of dust emissions.

When freshly processed aggregate is loaded onto a storage pile, its potential for dust emissions is at a maximum. Fines are easily disaggregated and released to the atmosphere upon exposure to air currents resulting from aggregate transfer or high winds.

As the aggregate weathers, however, the potential for dust emissions is greatly reduced. Moisture causes aggregation and cementation of fines to the surfaces of large particles. A significant rainfall soaks the interior of the pile and the drying process is very slow.

Construction Sites

Heavy construction is a source of dust emissions which may have substantial temporary impact on air quality. Building and road construction are the prevalent construction categories with the highest emissions potential.

Emissions are generated by a wide variety of operations over the duration of the construction of a building or road. These include land clearing, blasting, ground excavation, cut and fill operations, and the construction of the facility itself. Dust emissions vary substantially from day to day depending on the level of activity, the specific operations and the prevailing weather. A large portion of the emissions result from the equipment traffic over temporary roads at the construction site.

In all of the above cases, dust generation from a mechanical contact process with the exposed surface is insensitive to the ambient wind speed. However, the wind speed does determine the drift distance of large dust particles and, therefore, the localized impact of the fugitive dust source.

On the other hand, the generation of suspended particulates by wind erosion of exposed surface is very sensitive to the wind speed. The total surface removal by wind erosion, which consists mostly of transport of large particles close to the ground, depends on the cube of the wind speed above a threshold value of about 12 mph.4/

OBJECTIVES

The principal objective of the investigation reported herein was the development of emission factors for estimating atmospheric dust emissions from the source categories listed above. In each case, the emission factors were to incorporate correction factors to account for major variations in emissions with source conditions. Correction factors would include the effect of geographical differences in surface properties and climate. An attendant objective was the development of field testing procedures for measurement of dust emission rate and the particle size distribution of suspended dust.

This report is organized by subject area as follows:

- Chapter 2 presents a summary of the published literature dealing with quantitative studies of fugitive dust emissions.
- Chapter 3 outlines the plume sampling techniques and the data reduction schemes used to derive emission factors.
- Chapters 4 - 7 present for the four source categories, a complete, self-contained discussion of the field testing and the calculated test results, and conclude with the presentation of the corrected emission factor.
- Chapter 8 discusses the development of an emissions inventory for the specified source categories.
- Chapter 9 states the conclusions of this investigation.

CHAPTER 2

SUMMARY OF PERTINENT LITERATURE

The literature search conducted as part of this program yielded only scattered quantitative information on the characteristics of fugitive dust sources. Most of the reported studies were directed to the characterization of dust generation from unpaved roads. Measurement of suspended particulate levels (by standard high-volume filtration) in the vicinity of a fugitive dust source has been the most commonly used technique for quantification of the source impact.

EMISSIONS FROM DIRT ROADS

In an early study by the Albuquerque Air Management Division,[5] dust emissions from a dirt road in Bernallilo County were measured. A small filtration sampler was positioned first at the edge of the road and then directly behind the test car which traveled at 30 mph. The measured concentrations, coupled with assumptions about the configuration of the plume, yielded an emission factor in the range of 0.5-0.7 lb/vehicle-mile.

The first effort to measure the particle size of dust emissions from an unpaved road was conducted by engineering students at the University of New Mexico,[6] at a site just north of the Albuquerque campus. A standard high-volume filtration unit and a rotorod impactor were positioned 60-90 ft downwind of the test road. During each 30-min test, a total of 50 passes of the (two) test cars were sampled. Meteorological data for the test period were obtained from the local weather bureau. Background dust levels were determined by sampling with no traffic on the road. Particle size distribution was determined by microscopic examination of rotorod impaction samples. Emission factors were calculated from test results by applying a dispersion equation to account for expansion of the dust cloud from the point of generation. The factor for particles smaller than 6 μm in diameter (i.e., particles which would remain suspended under dry, windy conditions) was 0.93 lb/vehicle-mile.

A detailed study of emissions from dirt roads was conducted by PEDCo-Environmental[7] on a test roadway near Santa Fe, New Mexico, and at two sites in Tucson, Arizona. At the primary test site in Santa Fe, a GCA beta-gauge detector was used to measure vertical concentration profiles at distances of 50-300 ft downwind of the road during each of six 1-hr tests. Standard high-volume filtration samplers were also operated at downwind locations during each test, to provide a basis for correcting the measurement of the beta-gauge detector to an equivalent high-volume measurement. The high-volume readings averaged 1.68 times the beta-gauge measurements with a correlation coefficient of 0.87. Several test vehicles were used to provide between 100 and 200 passes per test. A recording wind instrument was operated near the site. Emission factors were calculated from corrected beta-gauge measurements and meteorological conditions, through the application of a dispersion equation for an infinite line source. The results are given in Table 1.

In addition to the intensive beta-gauge study, longer term (24- and 48-hr) high-volume dust samples were collected over a period of 2 months. Andersen high-volume cascade impactors were operated during 48-hr periods to measure particle size distribution of suspended dust. The purpose of this longer term study was to measure the impact of normal road traffic and, in particular, to determine the contribution of traffic dust emissions to the total suspended dust level in the vicinity of the test road.

Identical high-volume measurements were conducted during the same 2-month period at the two test sites in Tucson, Arizona. Application of the dispersion formulae to data from the Tucson sites for days when the wind conditions were fairly constant, yielded apparent emission factors (scaled against the traffic load) ranging from 4-6 lb/vehicle-mile. Taking into account the contributions of background dust and the low-level of wind erosion from the test roadways, the investigators concluded that there was substantial uniformity in emission rates from the three roads, in spite of differences in geographical location and traffic patterns.

The results of the particle size measurements for the three PEDCo sites were as follows:

	Suspended Particulate Mass < 3.3 μm (%)
Santa Fe	48
Tucson A	37
Tucson B	36

Table 1. TESTS OF EMISSIONS FROM UNPAVED ROADS

Site	Type of Road	Vehicle Speed (mph)	Sampler Type	Sampler Location	No. of Tests	Passes per Test	Emission Factor (lb/vehicle-mile)	Dust Size Cut-Off
Bernalillo County, New Mexico[5]	Dirt	30	Small filter	In plume	2	--	0.5 - 0.7	--
University of New Mexico[6]	Dirt	25	Hi-vol filter Rotorod	60-90 ft from road	2	50	0.93 0.04	< 6 µm < 3 µm
Santa Fe, New Mexico[7]	Dirt	15	Beta gauge	50-300 ft from road	1	150	0.67	--
		25	Hi-vol filters		1	240	1.0	--
		35	Hi-vol cascade impactor		3	200	2.0	--
		40			1	130	3.5	--
Poweshiek County, Iowa[8]	Dirt	--	Dustfall containers	Shoulder to 500 ft from road	1	3,000	5.5	--
Duwamish Valley, Washington[9]	Gravel	10	Isokinetic cascade impactor	7 ft behind automobile	2	--	2.2	--
							0.41	< 10 µm
							0.11	< 2 µm
		20			25	--	8.5	--
							2.3	< 10 µm
							0.29	< 2 µm
		30			2	--	13.9	--
							5.2	< 10 µm
							0.43	< 2 µm
	Gravel	20			1	--	8.8	--
							2.4	< 10 µm

Recently, Hoover[8] reported the results of the measurement of dust deposition near the edge of a test gravel road in Poweshiek County, Iowa. Dustfall collectors were positioned 3 ft above the ground and at distances (along a line perpendicular to the test road) ranging from 12 ft (shoulder) to 500 ft from the center line of the road. The containers were left in place for 21 days. Based on the amount of dust which settled within 500 ft of the road, the calculated emission rate was 5.5 lb/vehicle-mile. The results at the primary test site were confirmed by the results at a site near Iowa State University in Ames.

EMISSIONS FROM GRAVEL ROADS

A definitive study of emissions from gravel roads was conducted by the Puget Sound Air Pollution Control Agency[9] on test roads in Seattle's Duwamish Valley. The primary sampling device was a University of Washington Mark II Cascade Impactor, which separated the particulate catch into size fractions. The impactor was operated isokinetically at successive grid points (5-10 min per point) on a rack which was towed behind the test car. Twenty-five tests were conducted for a vehicle speed of 20 mph, with an average dust concentration of 370 mg/m^3 in the plume; tests were also run at 10 and 30 mph. The test results are shown in Table 1. As indicated, the total emissions factor and the size distribution for the two gravel roads tested at 20 mph are nearly identical.

Also worthy of mention is Sehmel's study[10] of particle resuspension from an asphalt road caused by car and truck traffic. Solid zinc sulfide, which was used as the tracer material, was applied to the 10-ft wide by 100-ft long area on one lane of a two-lane seasoned asphalt road. Filtration samplers (nonisokinetic), mounted on 8-ft towers, and ground-level deposition samplers were positioned in an array at distances of 3.5-100 ft downwind from the edge of the test area. A meteorological tower with a vector vane at 3-ft elevation and 3-cup anemometers at 1- and 7-ft elevations, was also operated downwind of the road.

The fraction of the tracer dust resuspended from the road per vehicle pass was calculated from a graphical integration of the downwind airborne tracer exposure and the tracer ground deposition. The mass balances were accurate within a factor of three. The following significant results were obtained:

1. The resuspension rate increased as the square of the vehicle speed and was independent of wind velocity.

2. Twenty to thirty percent of the particulate mass resuspended was deposited on the ground within 20 to 30 ft of the road.

3. The relative deposition rate passed through a minimum for a vehicle speed of 30 mph.

EMISSIONS FROM AGRICULTURAL AND CONSTRUCTION ACTIVITIES

The only available data on dust emissions from agricultural and construction activities were generated in the study, mentioned above, by PEDCo-Environmental.[7] At agricultural sites in Five Points, California, and Mesa, Arizona, standard high-volume filtration samplers were operated for a period of 2 months downwind (based on prevailing wind direction) of the test sites. Atmospheric dispersion formulae were used to calculate emission factors from the measured increase in particulate concentration (downwind minus upwind value) for selected days when the wind direction matched the alignment of the samplers. It was assumed that each sampler measured emissions from a test area of about 500 acres. The resulting factors, which were judged to be strongly affected by wind erosion emissions, ranged from about 1-2 tons/acre/year.

PEDCo's tests of emissions from residential construction activities[7] will be discussed thoroughly in Chapter 6.

No quantitative data were found for dust emissions from aggregate storage piles. An estimated value of 10 lb/ton for storage pile losses has been reported.[11]

CHAPTER 3

DUST EMISSION SAMPLING STRATEGY

This chapter summarizes the sampling strategy which was utilized for each source type. In particular, the dust emission sampling techniques are described and the schemes for calculating source emission rates from the field measurements are presented.

EMISSIONS FROM AGRICULTURAL TILLING AND UNPAVED ROADS

An agricultural implement tilling a field or a vehicle traveling an unpaved road may be treated as a moving point source which emits dust at a relatively constant rate. If the mean wind direction is roughly perpendicular to the path of motion of the point source, the dust plume drifts laterally as shown in Figure 1. As the plume is convected by the mean wind, atmospheric turbulence effectively disperses fine particles (and, to a lesser extent, moderate-sized particles) over an increasing cross-sectional area. The large particles settle to the ground as a result of the dominance of gravitational and inertial forces over turbulent mixing forces.

Since there is no net transport of dust in the direction of equipment motion, the settled and airborne dust within an incremental length in the direction of source motion directly represents what was emitted by an equivalent length of disturbed surface. This may be expressed as a mass balance which traces the fate of the dust emissions.

In the case of emissions from an agricultural tilling operation, the mass balance per unit length of tillage path is as follows:

$$\text{Dust generated by N implement passes}^{*} = \text{Dust deposition} + \text{Integrated atmospheric exposure} ,$$

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* Over adjacent strips of land.

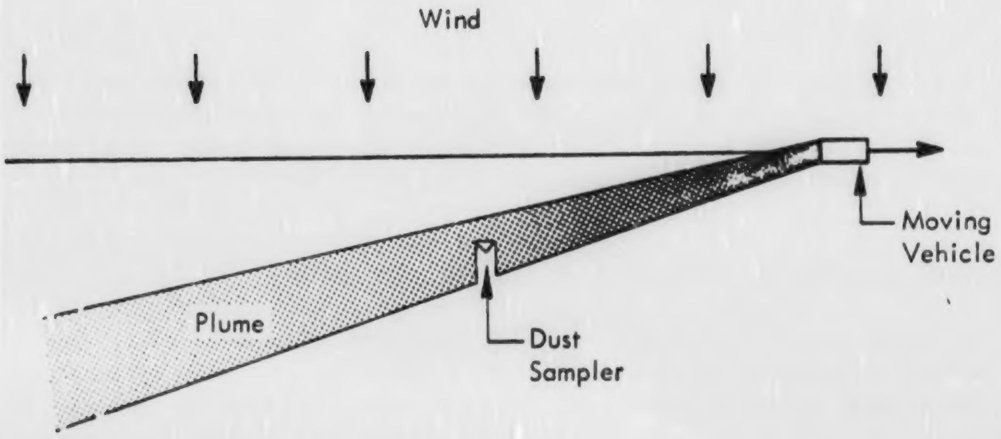
Wind
Moving Vehicle
Plume
Dust Sampler

Figure 1. Overhead view of dust plume from moving point source.

or

$$e_a bN = \int_0^{x_p} D(x)dx + \int_0^{\infty} \frac{m(h)}{a} dh \quad ,$$

where e_a = agricultural dust emission factor (mass/area),
b = working width of implement (length),
D = dust deposition (mass/length squared),
x = distance downwind from the source (length),
x_p = location of exposure sampler (length),
m = dust catch by exposure sampler after subtraction of background contribution, measured at x_p (mass),
a = intake area of exposure sampler (length squared), and
h = height above ground (length).

The exposure $\frac{m}{a}$ is the integrated passage of airborne dust per area normal to the direction of passage. The background contribution to the exposure is given by

$$m_b = QC_b \, ,$$

where Q = volume of air sampled (length cubed), and
C_b = background dust concentration measured upwind of the source (mass/length cubed).

In the case of emissions from an unpaved road, the mass balance per unit length of road is as follows:

$$\text{Dust generated by N vehicle passes} = \text{Dust deposition} + \text{Integrated atmospheric exposure} \quad ,$$

or

$$e_r N = \int_0^{x_p} D(x)dx + \int_0^{\infty} \frac{m(h)}{a} dh \quad ,$$

where e_r = road dust emission factor (mass/length-vehicle), and the other symbols are as defined above.

In order to collect a representative sample of airborne particulate, the sampling rate must be isokinetic; that is, the streamlines, along which the air flows as it passes into the sampler, must be rectilinear. Two requirements must be met to achieve isokinesis:

1. The magnitude of the sampling velocity must equal the local mean wind speed; and

2. The sampling intake must be perpendicular to the wind vector.

Near the surface, the mean wind speed has been found to increase in proportion to the logarithm of the height.

$$U = ku_*\ln(h/h_o),$$

where k = von Karman's constant (0.4 for clear fluids),
u_* = friction velocity, and
h_o = apparent roughness height.

The roughness height of a plowed field is approximately equal to 1 cm.[12]

The wind speed profile over a larger vertical range may also be expressed as a power law,

$$U = U_1\left(\frac{h}{h_1}\right)^n ,$$

where U_1 = wind speed at reference height h_1, and
$n = 0.2$ for daytime conditions.[13]

Using $h_1 = 12$ ft as the reference height, the above expressions may be rewritten as follows:

log law	power law
$\frac{U}{U_{12}} = \frac{\ln(336\ h)}{5.90}$	$\frac{U}{U_{12}} = \left(\frac{h}{12}\right)^{0.2}$.

As shown in Figure 2, over the range of height utilized for exposure sampling (3 ft $\leq h <$ 12 ft), the two expressions agree to within about 1%.

If the sampling is nonisokinetic by virtue of the failure to meet condition 1 above, corrections must be made to the nonisokinetic particulate catch m_n.

$m = m_n\left(\frac{u}{U}\right)$	fine particles ($d < 5$ µm)
$m = m_n$	coarse particles ($d > 50$ µm) ,

where U = the local wind approach speed and
u = the magnitude of the sampling velocity at the sampler intake.

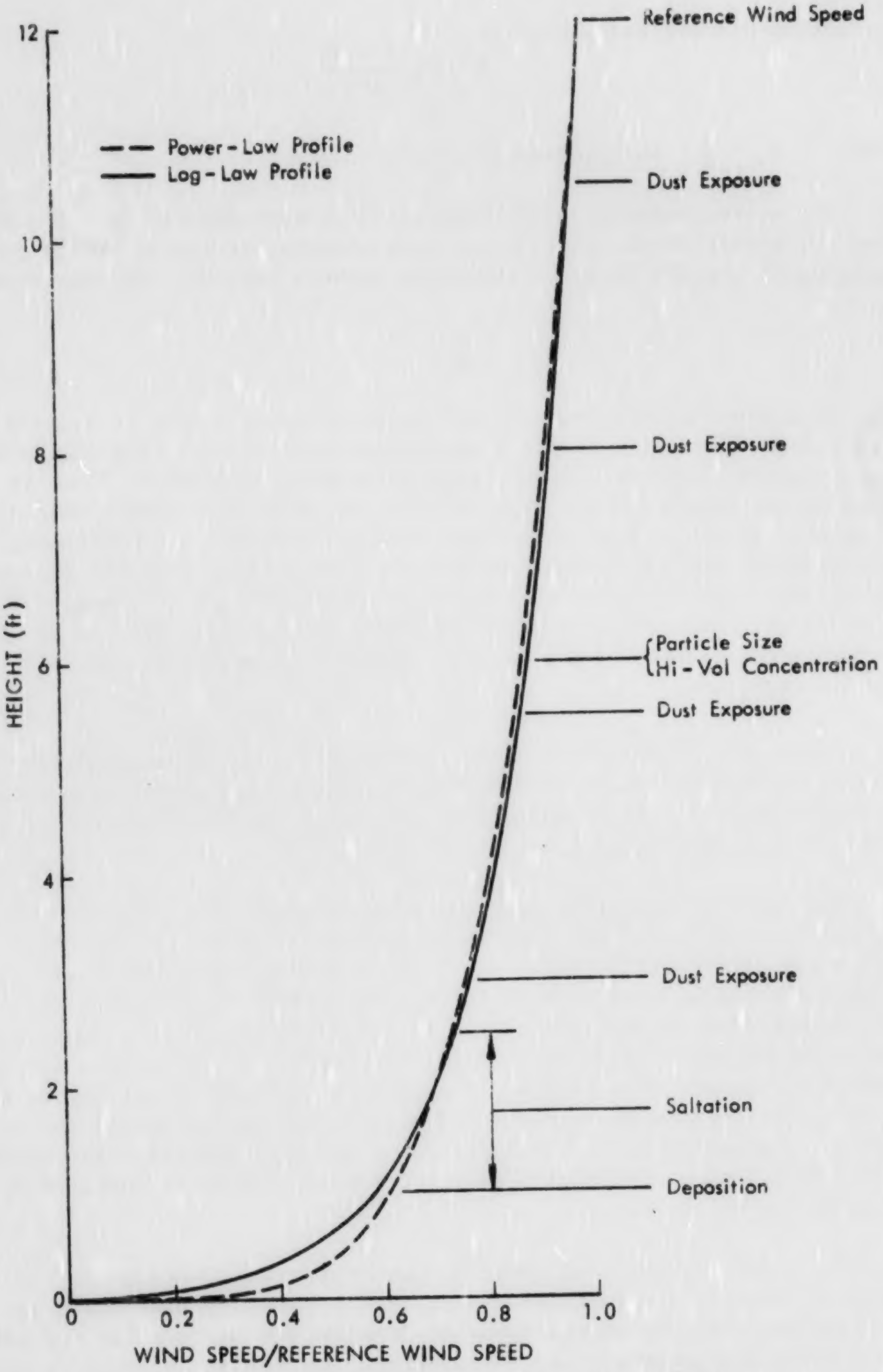

Figure 2. Comparison of wind speed profiles.

For intermediate-sized particles,

$$m = m_n\left(\frac{1 + F_I}{2F_I}\right) \quad ,$$

where $F_I = \frac{u}{U}$ = the isokinetic ratio.

The above connections for nonisokinesis were derived from the correction for nonisokinetic particulate concentration presented in the Federal Register[14] and the basic relationship between exposure and concentration (C):

$$\frac{m}{a} = CU \quad .$$

Most conventional samplers for airborne particulates (e.g., the high-volume filtration sampler) are nondirectional with sampling intakes usually aimed downward. While particles smaller than about 10 µm in diameter are readily drawn into the sampler, particles larger than about 50 µm (for moderate wind speed) are sampled with very low efficiency. Consequently, the large particle mode (> 3 µm diameter) of the typical bimodal size distribution of atmospheric particulate[15] is largely missed, even though it may comprise more than half of the total mass in an area influenced by sources of dispersion* particulate aerosol (e.g., soil and mineral particles).

Since most of the mass of the particles emitted by agricultural tilling and unpaved roads would fall into the large particle mode, conventional samplers were judged to be less suitable than isokinetic samplers for the subject program.

The exposure profiling unit which was designed for this study is pictured in Figure 3. It consists of a vertical array of isokinetic high-volume filtration devices attached to a mobile support tower. Each sampler accommodates an 8-in. x 10-in. glass fiber filter (Type E). The reduced sampling intake area (2 in. x 2 in.) increases the allowable wind speed maximum for isokinetic sampling to 20 mph. Flexible hose (4-in. diameter) connects each sampler to a suction manifold. Each leg of the manifold is fitted with a calibrated orifice (connected to 0-1 in w.c. inclined manometer) and a butterfly valve for flow control. The vacuum source is a 2-hp centrifugal blower. Electrical power is supplied by a gasoline-engine generator.

The exposure profiling tower was positioned close enough to the source to measure the vertical extent of the plume (by reasonable extrapolation), but far enough downwind from the source to allow for adequate plume development prior to sampling. The minimum acceptable plume

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* Generated by mechanical forces.

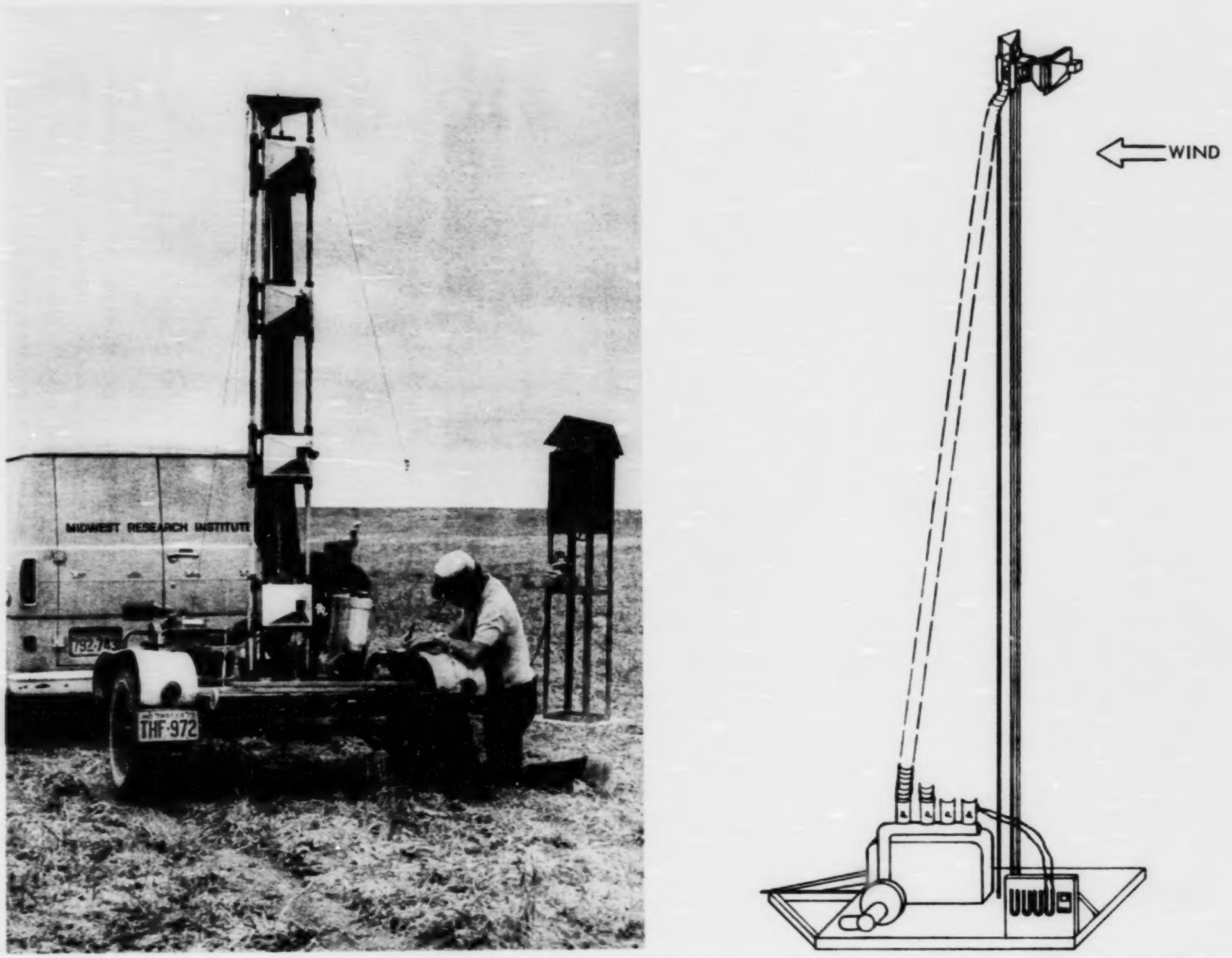
MIDWEST RESEARCH INSTITUTE
THF-972
WIND

Figure 3. MRI dust exposure profiler.

travel distance from the downwind edge of the source was judged to be about 20 ft. (In the case of agricultural tilling, the source-to-sampler distance was maintained by advancing the profiling tower downwind between tillage implement passes.) Since dust-producing conditions were fairly uniform along the emitting surface, the specific sampling location in the direction of source motion was not critical.

Dust deposition was measured by standard 1-ft high dustfall buckets, which were positioned downwind of the source along a line perpendicular to the direction of source motion. The deposition samplers may also have collected some particles transported by saltation.

Sand-sized dust particles injected into the atmosphere by a tilling operation or by a vehicle traveling an unpaved road may be transported by "saltation"* over substantial distances if the wind velocity exceeds the wind erosion threshold. Since these particles are never truly suspended in the atmosphere, they are not considered part of the atmospheric dust emissions from a fugitive dust source. Nevertheless, limited measurements of saltation dust would yield useful information on the magnitude of saltation transport relative to suspended dust transport and saltation transport by wind erosion.

The saltation catcher which was designed and fabricated for this study, consisted of a dustfall bucket fitted with an 18-in. high sheet metal tube with a 1-in. wide vertical sampling slot. The slot is pointed upwind and captures saltating particles within the height interval of 12-30 in. The capture efficiency is estimated to be about 50%.16/

The Andersen high-volume cascade impactor was selected as the primary device for suspended dust particle sizing. The impactor is designed to be attached to a standard high-volume sampler. It has five glass fiber impaction surfaces, followed by a glass fiber back-up filter. A sampling height of 6 ft was chosen to represent average plume conditions and to correspond to the ground level breathing zone.

The standard high-volume filtration unit17/ was selected for measurement of background (upwind) dust concentration. The 3-ft sampling height is above the saltation zone and should, in the absence of wind erosion, trap most of the background particulate. Limited downwind measurements of suspended dust by standard high-volume filtration were also included in the experimental design as a check on the large-particle trapping efficiency of the standard high-volume sampler.

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* Saltation is particle motion by a series of jumps.

EMISSIONS FROM AGGREGATE STORAGE PILES

A distribution of aggregate storage piles with associated truck traffic and transfer operations is a diffuse area source. Emissions vary substantially from day to day because of variations in consumer demand. Therefore, emissions must be sampled over a widespread area for a period of several days. Because of changes in wind speed and direction over extended time periods, isokinetic sampling of aggregate storage emissions is a virtual impossibility.

Standard high-volume filtration units[17] with wind-direction activators were selected as most suitable for sampling of diffuse aggregate storage operations. Sampling units were strategically positioned so that when the wind had a nonzero component in the prevailing wind direction for the locality (a condition for activation of the samplers), one unit was upwind of the storage area and the others were distributed downwind of the storage area. Emissions were calculated from the measured average downwind flux (average concentration multiplied by atmospheric ventilation rate) of aggregate dust, over an assumed cross-sectional transport area.

The greatest intensity of dust emissions in the aggregate storage cycle occurs during the transfer of material onto the stockpiles and the loadout of material from stockpiles into trucks.

In order to measure the dust emission rate from the loadout operation, a special sampling apparatus was designed and constructed. This apparatus, shown in Figure 4, consisted of a grid of six samplers mounted on top of a mobile van and controlled by auxiliary equipment inside the van.

Dust-laden air passes into the intake nozzle (1/2-in. diameter by 4 in. long) of each sampler and through the dust collection medium--a circular glass fiber filter (2-in. diameter). The filtered air then passes through a matched critical orifice, common manifold, vacuum pump, and dry test meter. Sampling rates were preset to be isokinetic for a 10-mph wind speed. The dry test meter provided a check on the total sample volume. Electrical power was supplied by a generator located on top of the van.

During testing, the sampling van was positioned downwind of the truck being loaded, as shown in Figure 5. The dust, which was generated when the high loader dumped into the truck, passed across the sampling grid.

In the case of emissions from aggregate loadout, the mass balance (neglecting deposition) is given by:

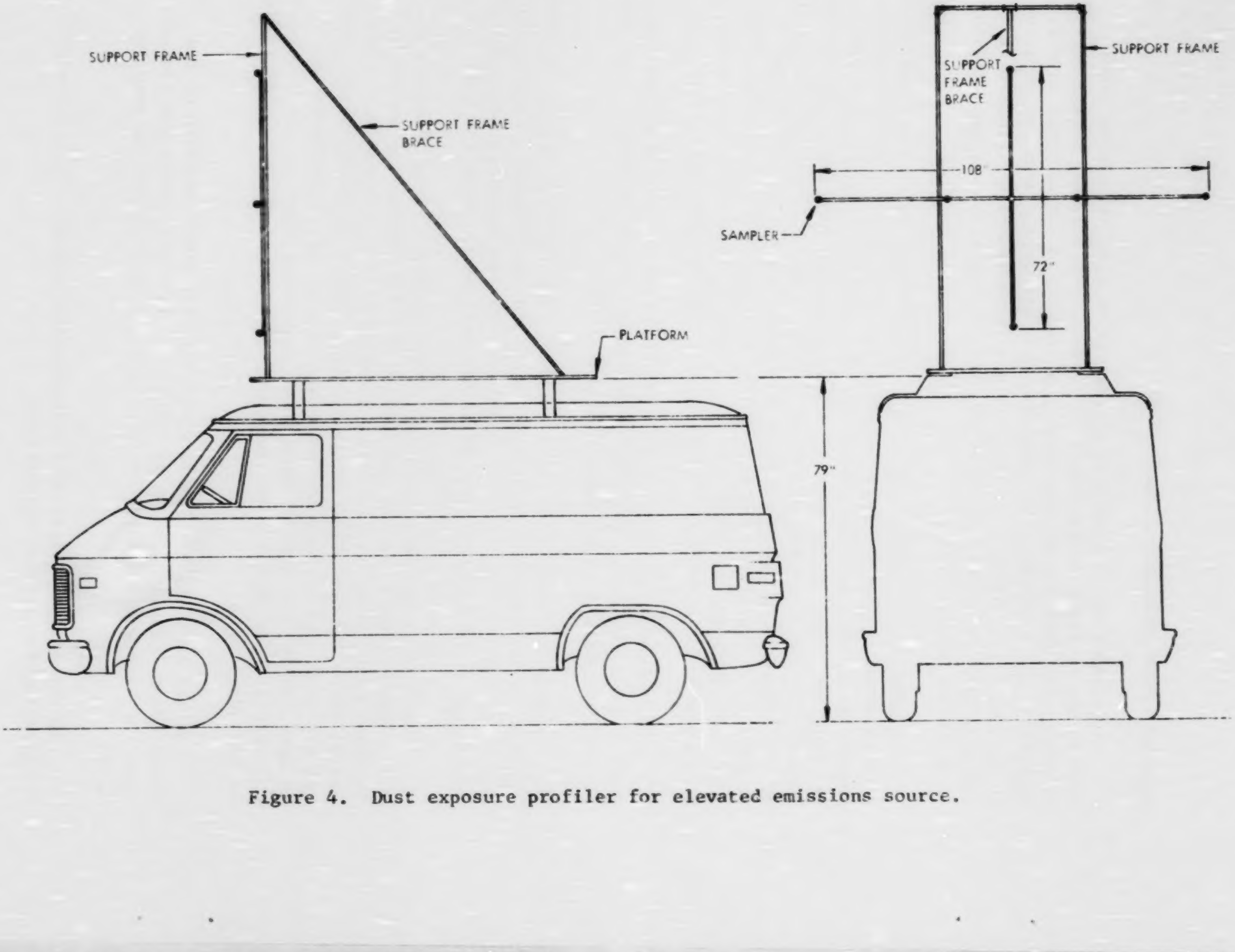
SUPPORT FRAME
SUPPORT FRAME BRACE
PLATFORM
SUPPORT FRAME
SUPPORT FRAME BRACE
108"
SAMPLER
72"
79"

Figure 4. Dust exposure profiler for elevated emissions source.

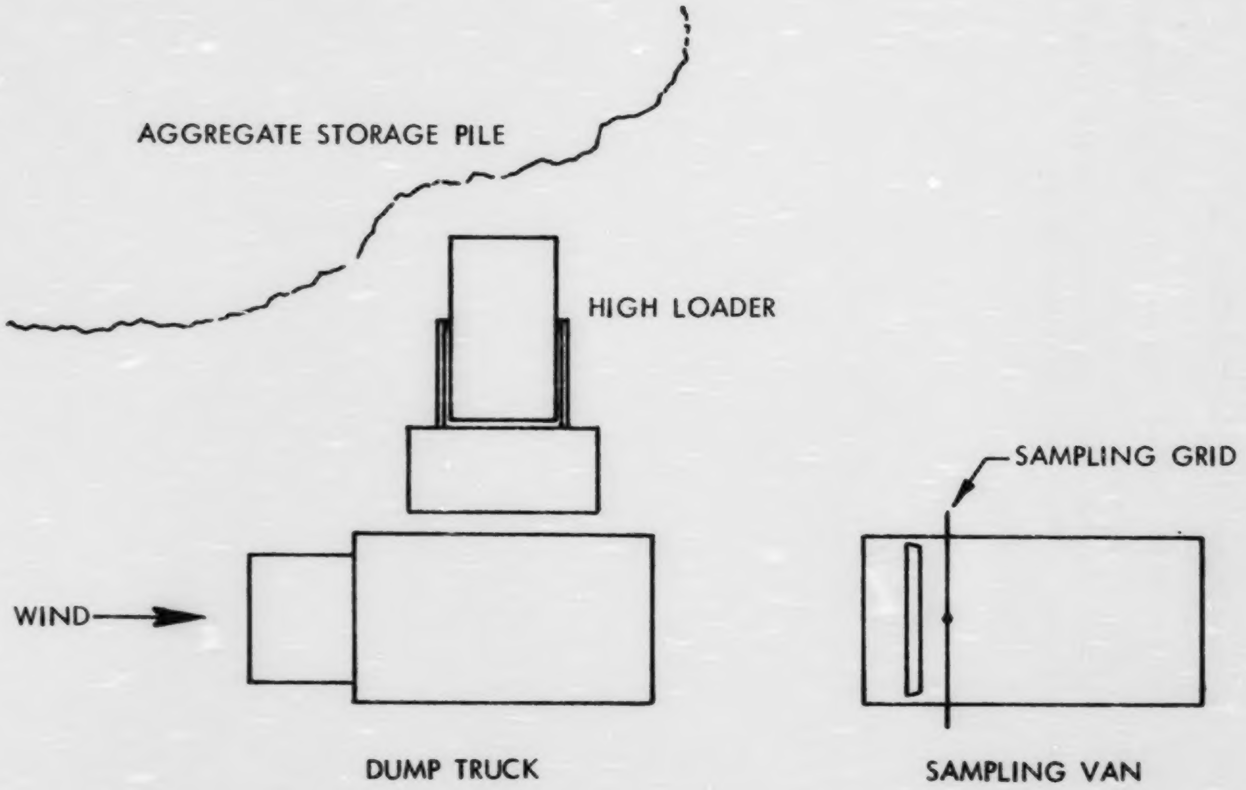
AGGREGATE STORAGE PILE
HIGH LOADER
SAMPLING GRID
WIND
DUMP TRUCK
SAMPLING VAN

Figure 5. Positioning of test equipment--aggregate loadout.

$$\text{Dust generated by aggregate loaded} = \text{Integrated atmospheric exposure}$$

or

$$e_p W = \int_{-\infty}^{\infty} \int_{o}^{\infty} \frac{m(h,w)}{a} dh\ dw \quad ,$$

where e_p = loadout dust emission factor (mass/weight loaded)
W = weight of aggregate loaded (mass)
w = lateral distance from center-line of truck (length)
and the other symbols are defined as above.

CHAPTER 4

UNPAVED ROAD EMISSIONS

SAMPLING SITE DESCRIPTION

Franklin County, Kansas, was selected for the study of atmospheric dust emissions from gravel roads; Morton and Wallace counties in Kansas, were selected for the study of emissions from dirt roads. The test roads were chosen on the basis of their representativeness of unpaved roads in the dry, windy area of the Great Plains.

Detailed descriptions of the individual test sites are given in the following paragraphs.

Gravel Road Sites

Two sites in Franklin County, Kansas, were selected for the study of atmospheric dust emissions from gravel roads. Franklin County is located in the east-central part of the state.

Site R1 was a lightly traveled section of east-west road located about 1 mile east of Williamsburg, Kansas; this road was covered with a considerable amount of loose gravel. Site R2 was a section of north-south county road located just north of a nearly completed section of Interstate 35; this road was well worn, with little loose gravel.

Dirt Road Sites

Two sites were selected for the study of atmospheric dust emissions from dirt roads--one in Morton County, Kansas, and the other in Wallace County, Kansas.

Site R3 was a section of east-west county road located in Morton County between T35S, R42W, Section 2, and T34S, R42W, Section 35. The soil type in the area was Richfield fine sandy loam. This road, although lightly traveled, had a large proportion of heavy truck traffic.

Site R4 was a section of north-south road located in Wallace County between T13S, R40W, Section 31, and T13S, R41W, Section 36. The soil in the area of this lightly traveled road was of the Keith/Colby silt loam association.

FIELD MEASUREMENTS

Field testing of dust emissions from unpaved roads was conducted at the Franklin County sites (R1 and R2) in April 1973, and at the Morton and Wallace counties sites (R3 and R4) in May and June 1973.

Table 2 specifies the kinds and frequencies of field measurements that were conducted during each run. "Composite" samples denote a mixture of single samples taken from several locations in the area; "integrated" samples are those taken at one location for the duration of the run.

Composite samples of in-place road dust were obtained by manually sweeping the loose material from lateral strips of road surface into plastic bags. Samples were returned to MRI for laboratory determination of texture and moisture content.

At the end of each run, the collected samples of dust emissions were carefully transferred to shipping containers within the MRI instrument van, to prevent dust losses. High-volume filters (from the MRI exposure profiler and from standard high-volume units) were folded and placed in individual folders. Dust that collected on the interior surfaces of each exposure probe was rinsed with distilled water into a glass jar. The contents of the deposition samplers were also rinsed into glass jars. Cascade impactor collection papers were left in place within each impactor unit.

Most of the traffic volume for each run was provided by local residents who were hired to drive their own vehicles at the prescribed speed over a 1/2-mile section of test road. Vehicle spacing was maintained to eliminate possible vehicle interaction effects on dust generation. As indicated in Table 3, all of the test vehicles were four-wheel vehicles--either passenger cars or pick-up trucks.

Table 4 presents information on the time of each run, the prevailing meteorological conditions and the vehicular traffic. Over the typical 1-hour test duration, meteorological conditions and traffic characteristics did not vary significantly.

Table 2. FIELD MEASUREMENTS--UNPAVED ROADS

Test Parameter	Units	Sampling Mode	Measurement Method
1. Meteorology			
a. Wind speed	mph	Continuous	Recording instrument at "background" station; sensors at reference height
b. Wind direction	deg	Continuous	
c. Cloud cover	%	Single	Visual observation
d. Temperature	°F	Single	Sling psychrometer
e. Relative humidity	%	Single	
2. Road Surface			
a. Type	--	Composite	Observation (photographs)
b. Texture	--	Composite	Dry sieving
c. Moisture content	%	Composite	Weight loss on oven drying
d. Embankments	--	Composite	Observation (photographs)
3. Vehicular Traffic			
a. Type	--	Multiple	Observation (car, truck, number of axles, etc.)
b. Count	--	Cumulative	Observation
4. Suspended Dust			
a. Exposure (vs height)	mg/in^2	Integrated	Isokinetic high-volume filtration (MRI method)
b. Size distribution (by weight)	μm	Integrated	Cascade Impaction
c. Concentration	$\mu g/m^3$	Integrated	High-volume filtration (EPA method[17])
d. Background concentration	$\mu g/m^3$	Integrated	High-volume filtration (EPA method[17])
e. Duration of sampling	min	Cumulative	Timing
5. Deposition (vs distance from source)	$lb/ft^2/hr$	Integrated	Dustfall buckets (ASTM method[18])

Table 3. VEHICLE MIX (Unpaved Roads)

				No. of Vehicle Passes							
				Test Vehicles			Normal Traffic				
								Trucks			
Run	Site	No. of Test Vehicles	Description of Test Vehicles	Cars	Trucks	Total	Cars	4-Wheel	Other	Total	% 4-Wheel Vehicles
1	R1	3	2 cars, 1 truck	108	54	162	3	1	2	6	98.8
2	R2	5	3 cars, 2 trucks (one with camper)	112	91	203	7	7	6	20	97.3
3	R2	5	3 cars, 2 trucks (one with camper)	144	109	253	11	7	2	20	99.1
4	R1	3	3 cars	148	0	148	--	--	12	12	>92.0
8	R3	4	3 cars, 1 pick-up truck	109	42	151	0	3	13	16	92.2
10	R3	5	3 cars, 2 pick-up trucks	71	60	131	0	0	1	1	91.7
13	R4	1	1 car	51	0	51	1	3	0	4	100.0

Table 4. EMISSIONS TEST PARAMETERS (Unpaved Roads)

Run	Site	Date	Time		Duration of Exposure Sampling (min)	Road Direction	Ambient Temp. (°F)	Wind Direction/ Speed (12 ft)	Cloud Cover (%)	Pasquill Stability[a]	Vehicle Speed (mph)	No. of Passes
			Start	Finish								
1	R1	4 April 1973	1522	1622	60	E-W	50	NNW/17 mph	75	D	30	168
2	R2	5 April 1973	1411	1511	60	N-S	60	SW/13 mph	0	C-D	30	223
3	R2	5 April 1973	1555	1655	60	N-S	63	SW/13 mph	0	C-D	40	273
4	R1	7 April 1973	0945	1215	150	E-W	46	N/15 mph[b]	100	D	30-35	160
8	R3	25 May 1973	1502	1602	60	E-W	85	S/19 mph	50	D	30	167
10	R3	6 June 1973	1141	1241	60	E-W	75	SW/10 mph[b]	0	B	40	132
13	R4	12 June 1973	1701	1801	60	N-S	75[b]	NE/10 mph[b]	80[b]	D	30	55

---

[a] Pasquill Stability Classes:[19]

A - Extremely unstable
B - Unstable
C - Slightly unstable
D - Neutral
E - Slightly stable
F - Stable to extremely stable

[b] Estimated value

Table 5 gives the locations (intake height and distance from road) of the various plume sampling devices that were used for each run. The dust particle size classifiers included two types of high-volume cascade impactors (Andersen and Sierra) operated within standard high-volume enclosures. The drift distance multiplier, given in the last column of the table, takes into account the effect of the horizontal wind-road angle on the plume travel distance.

TEST RESULTS

Dust samples from the field tests were analyzed gravimetrically in the laboratory. Filters were conditioned in a controlled temperature-humidity environment prior to weighing. Water rinses from exposure probes, deposition samplers and saltation catchers were evaporated on a steam bath in tared beakers, after which the beakers were conditioned and weighed.

The measured dust emission from the tests of unpaved roads are presented in Table 6. The dust quantities are the amounts generated per vehicle-mile of travel.

The total dust emissions for a given run are the sum of the integrated exposure (above the background exposure) and the amount of deposition between the edge of the road and the downwind location of the exposure profiler.

The suspended dust measurements used to compute the integrated exposure are presented in Table 7. Point values of exposure are converted to concentration. The concentration measured by the standard high-volume unit, which was positioned to the side of the profiler, is also presented. The exposure profiles are shown in Figure 6.

Through regression analysis of all of the deposition measurements the local deposition (scaled against the integrated exposure measurements) was found to correlate best with plume travel time. The generalized deposition distribution (vs travel time) exhibited a sharp decrease within the first second of travel time followed by a gradual decay with increasing travel time. Because no simple (two-parameter) mathematical expression described the abrupt change in the deposition distribution, it was decided to treat only the gradual decay portion of the distribution.

Table 5. DUST EMISSION SAMPLER LOCATIONS
(Unpaved Roads)

		Perpendicular Distance from Downwind Edge of Unpaved Road (ft)					
Run	Site	MRI Exposure Profiler[a]	Particle Size Classifier (h = 6 ft)[b]	Deposition Sampler (h = 1 ft)	Saltation Catcher ($1 \leq h \leq 2.5$ ft)	Standard Hi-Vol Sampler (h = 6 ft)	Drift Distance Multiplier[c]
1	R1	20	--	9	--	--	1.1
2	R2	24	--	6.5, 13	--	24	1.4
3	R2	24	--	6.5, 13	--	24	1.4
4	R1	--	18 (SI)	--	--	--	1.0
8	R3	20	--	8, 90-100	20	20	1.0
10	R3	20	20 (SI, AI, AC)	10, 20, 50	20	--	1.4
13	R4	20	20 (AI)	20	20	--	1.4

---

a/ Sampling heights: h = 3, 5.5, 8, and 10.5 ft above grade.

b/ Sizing device: SI = Sierra impactor
AC = Aerotec cyclone
AI = Andersen impactor

c/ Ratio of drift distance to perpendicular distance.

Table 6. MEASURED DUST EMISSIONS (Unpaved Roads)

Run	Site	Background Concentration ($\mu g/m^3$)	Wind Speed (mph)	Plume Travel Time to Profiler (sec)	Unit Dust Catch (lb/vehicle-mile) Saltation	Deposition	Integrated Exposure	Hi-Vol MMD[a] (μm)
1	R1	46.9	17	0.88	--	2.1	9.98	--
2	R2	38.5	13	1.8	--	1.1	10.3	--
3	R2	38.5	13	1.8	--	2.1	13.9	--
4	R1	--	15[b]	--	--	--	--	--
8	R3	102.0	19	0.72	1.7	350	16.3	--
10	R3	--	10[b]	1.9	0.26	5.6	6.03	2.3
13	R4	--	10[b]	1.9	0.41	45.1	55.9	2.5

---

[a] Mass mean diameter of suspended dust, measured with Andersen high-volume cascade impactor.

[b] Estimated value.

Table 7. PLUME SAMPLING DATA (Unpaved Roads)

Run	Site	Height (ft)	Sampling Rate (cfm)	Concentration (mg/m^3)	Unit Exposure (mg/in.^{2}/vehicle)
1[a]	R1	10.5	29.0	0.90	0.082
		8	27.5	3.33	0.289
		5.5	26.0	7.20	0.591
		3	24.1	8.13	0.619
2[a]	R2	10.5	24.1	2.82	0.162
		8	22.7	6.60	0.357
		6[a]	49.3	6.53	--
		5.5	21.4	10.8	0.552
		3	19.3	18.4	0.843
3[a]	R2	10.5	24.1	3.66	0.172
		8	22.7	10.4	0.459
		6[b]	46.5	9.50	--
		5.5	21.4	18.1	0.753
		3	19.3	30.9	1.158
8	R3	10.5	35.7	2.65	0.238
		8	34.5	4.81	0.418
		6[b]	43.0	1.37	--
		5.5	32.2	9.08	0.737
		3	28.2	21.9	1.56
10	R3	10.5	24.1	1.94	0.150
		8	22.8	3.29	0.242
		6[c]	20.0	2.74	--
		6[d]	38.9	2.31	--
		5.5	21.3	4.10	0.281
		3	19.2	8.27	0.511
13	R4	10.5	24.3	4.61	0.866
		8	23.2	9.20	1.65
		6[c]	20.5	8.61	--
		5.5	21.5	16.4	2.73
		3	19.2	28.0	4.15

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[a] Sampling rate was corrected for 80% isokinetic.

[b] Standard high-volume sampler.

[c] Andersen impactor.

[d] Sierra impactor.

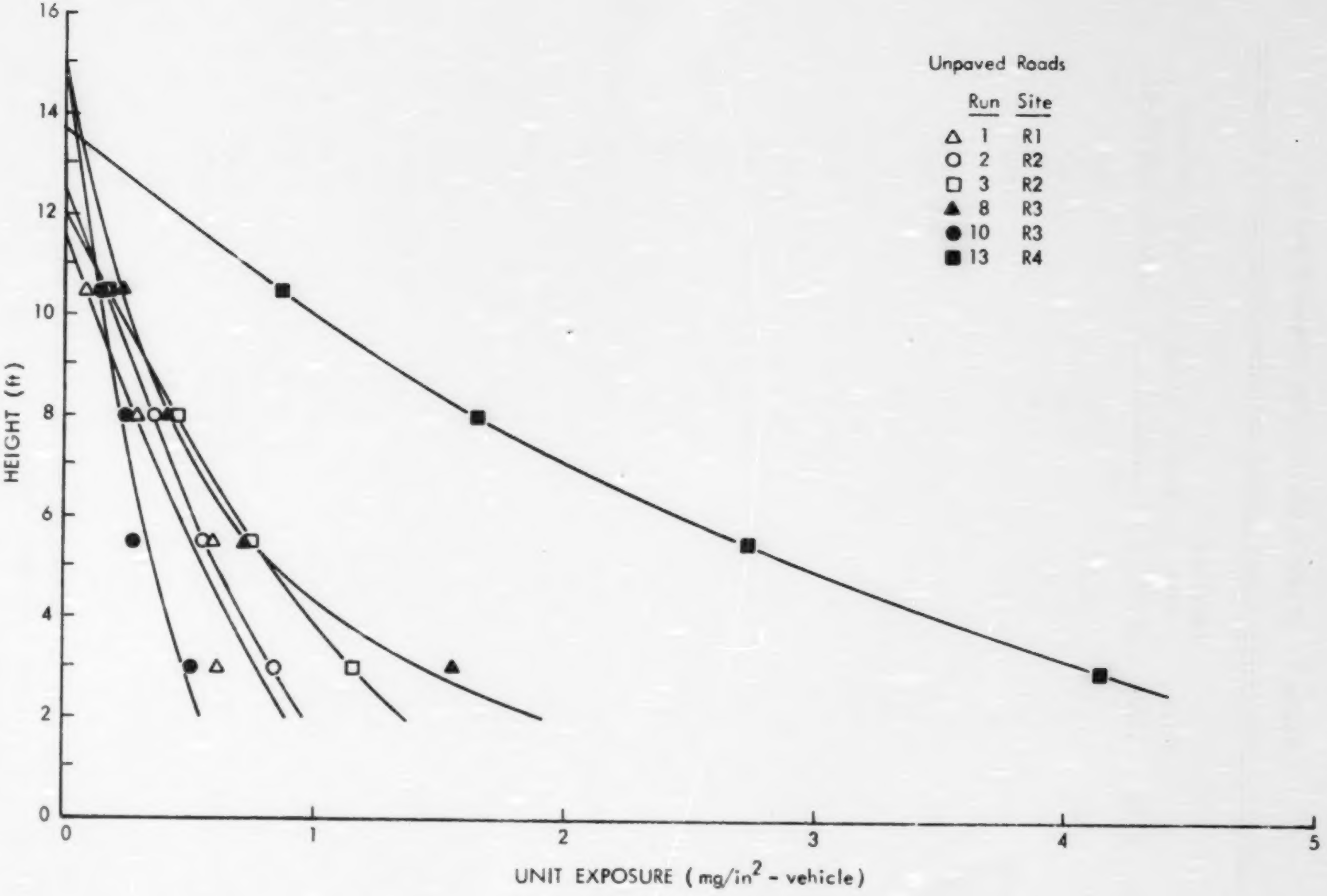

Figure 6. Exposure profiles--unpaved roads.

Deposition measurements for distances greater than 8-10 ft from the road edge (i.e., beyond the high fallout strip adjacent to the road) were fit to the function $\alpha \exp(-\beta t)$ where α and β are parameters and t is the travel time. If only one deposition measurement were available, an average value of β from the other runs was used and a new value of α was determined.

The measurements of dust transport by saltation are shown only for purposes of comparison. Saltation, which is confined to about 30 in. of height, is not considered to be a form of atmospheric emissions. Also it should be noted that the saltation catchers used in this study did not sample below 12 in. above the ground.

Also given in Table 6 is the mass mean diameter of suspended dust particles measured with the Andersen high-volume cascade impactor. The diameter values are aerodynamic measures which treat particles as equivalent spheres with a density of 2.5 gm/cm^3. The complete size distributions are shown in Figure 7.

Two potentially significant sources of error in the particle size measurements deserve special mention:

1. The impactor samples nonisokinetically through the high-volume enclosure openings and captures large particles with low efficiency.

2. Unlike urban aerosol, road dust particles are dry and brittle and are subject to bouncing and reentrainment from impaction surfaces. Recent empirical evidence obtained by Sehmel[20] indicates that this effect is most pronounced for particles larger than 20 µm in diameter.

Both of these factors cause apparent size determinations to be biased in the direction of small diameter. The second factor seemed to be substantial with the Sierra slotted impactor (MMD $\approx$ 1 µm); for this reason the Sierra measurements were not used.

Table 8 gives the results of the laboratory analyses of the samples of loose material from the road surface. Moisture content was determined by weight loss on oven drying and particle size analysis by dry sieving.

The low moisture content of the surface material is indicative of its tendency to dry quickly after the nighttime addition of moisture from the road substrate.

The particle size analyses of the road surface samples indicate that the well-worn gravel road (R2) had more sand-sized fines than the less-traveled gravel road (R1), but both had about the same percentage of silt. The dirt road in Wallace County (R4) had a much larger percentage of silt than the gravel roads.

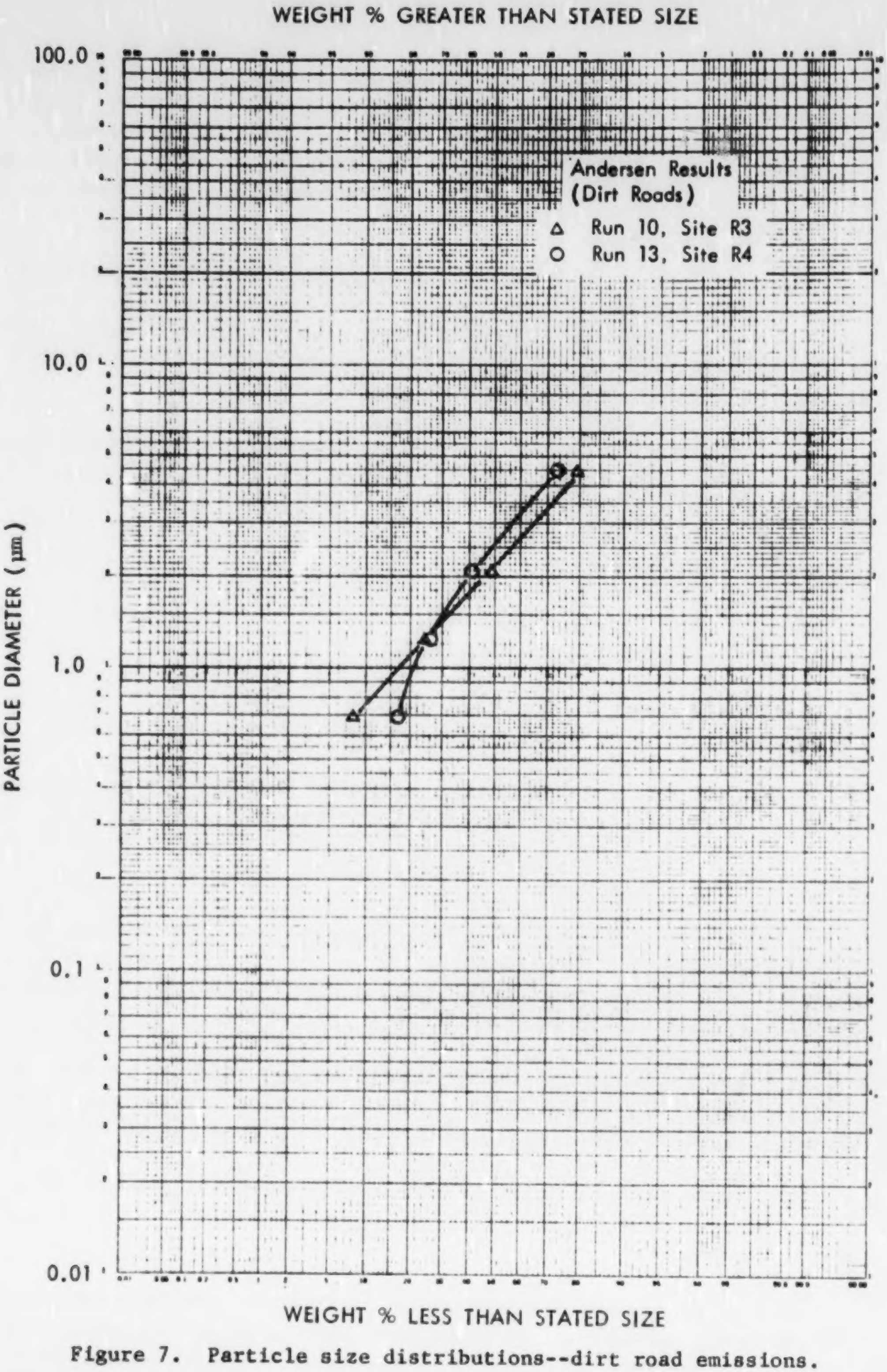

Figure 7. Particle size distributions--dirt road emissions.

Table 8. ROAD SURFACE PROPERTIES (Unpaved Roads)

					Surface Texture (% by weight)[a]			
Run	Site	Surface Type	Surface Moisture (%)	Loose Surface Material (lb/ft^2)	Gravel (>2000 μm)	Coarse Sand (2000-420 μm)	Fine Sand (420-74 μm)	Silt (<74 μm)
1	R1	Gravel	3.8	1.4	38	29	21	12
2	R2	Gravel	1.4	1.0	29	31	26	13
3	R2	Gravel	1.4	1.0	29	31	26	13
4	R1	Gravel	---	1.4	38	29	21	12
8	R3	Dirt	---	---	--	--	--	--
10	R3	Dirt	---	---	--	--	--	--
13	R4	Dirt	3.2	2.2	12	12	8	68

---

[a] Determined by dry sieving method; results accurate to within ± 5% of true value (e.g., 12 ± 0.6).

The size distributions for the road surface samples are plotted in Figure 8. The samples from dirt road R4 was also analyzed for size distribution by the Buoyocous hydrometer method[21] with sodium hexametaphosphate as a dispersing agent. As shown in the figure, the hydrometer method disaggregates clay particles and produces a better representation of the "ultimate" size distribution of the material.

COMPUTED EMISSION FACTORS

The environmental impact of dust emissions from unpaved roads varies greatly with particle size. Large particles ($d > 100$ µm) drift short distances from the road during the settling process and create mainly a nuisance problem. On the other hand fine particles ($d < 2$ µm), which represent a potential health hazard and which effectively reduce atmospheric visibility, are dispersed to high altitudes, and may remain suspended for long periods of time. Thus, it is imperative that emission factors be developed for specific particle size ranges.

Gillette and Blifford[16] have recently developed criteria for the maximum sized particle which can be supported in suspension by a given turbulent wind and the minimum sized particle which settles unimpeded by the vertical velocity fluctuations of the air. These size cut-offs are related to specific ratios of particle settling velocity to friction velocity. This work is reviewed further in Chapter 8.

The drift distance as a function of particle size may be estimated from the initial height of injection into the atmosphere, the settling velocity and the mean wind speed. For emission from unpaved roads, the average height of injection is assumed to be 5 ft. The mean wind speed at 5 ft is related to the speed at the 12-ft reference height through the profile presented in Figure 2. The settling velocity is based on the drag coefficient for spheres[22] and a particle density of 2.5 g/cm^3.[23]

Figure 9 shows the calculated drift distance as a function of particle size and mean wind speed. The boundaries of the settling-suspension regimes were derived from the Gillette-Blifford criteria[16] using a friction velocity based on a roughness height of 1 cm.[12] As indicated in the figure, particles which are not significantly affected by atmospheric turbulence will settle to the ground within a drift distance of 15 ft. Because particles which drift beyond 15 ft are affected by vertical velocity fluctuations, the average drift distance will be greater than the values shown.

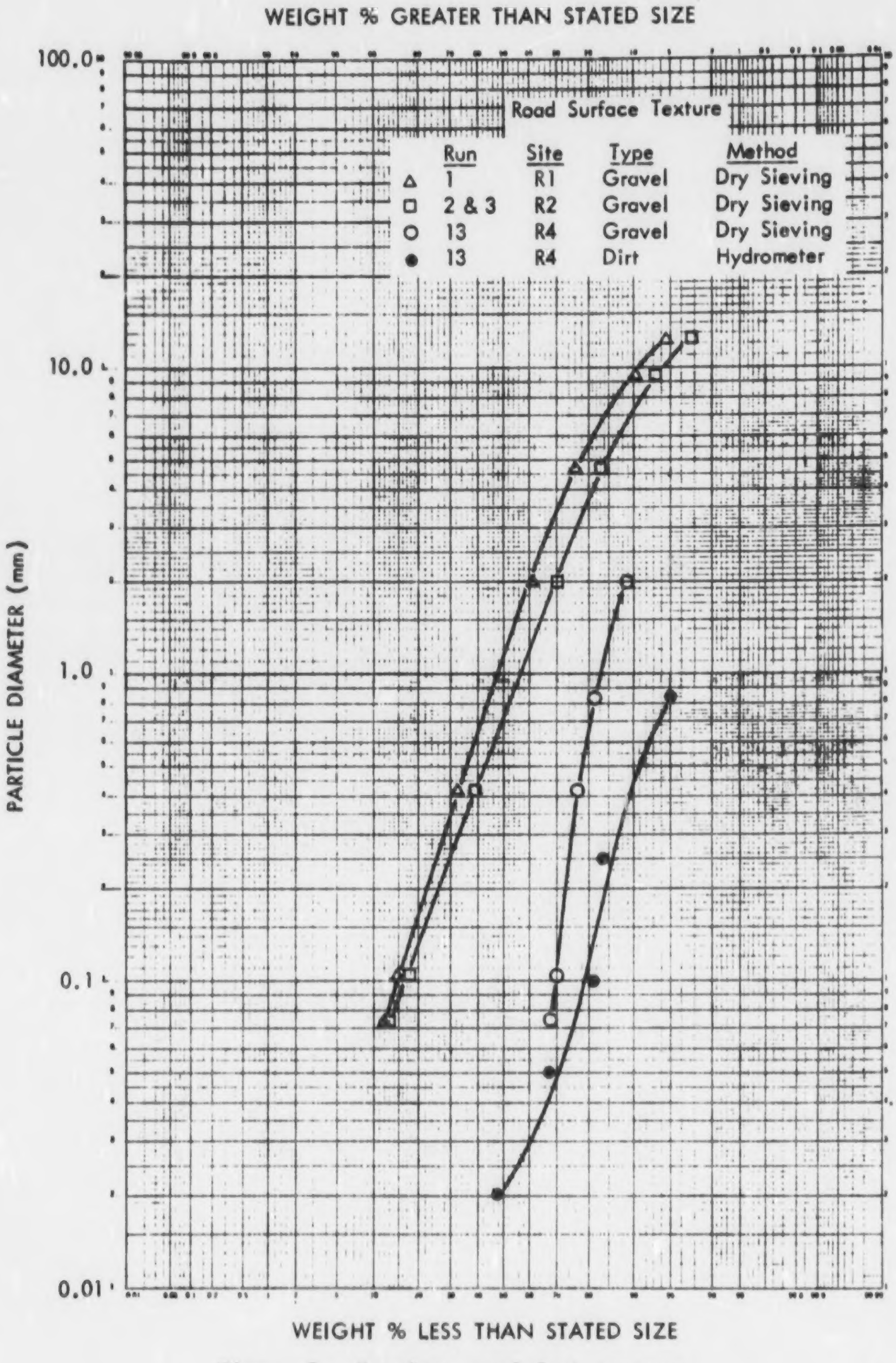

Figure 8. In-place road dust texture.

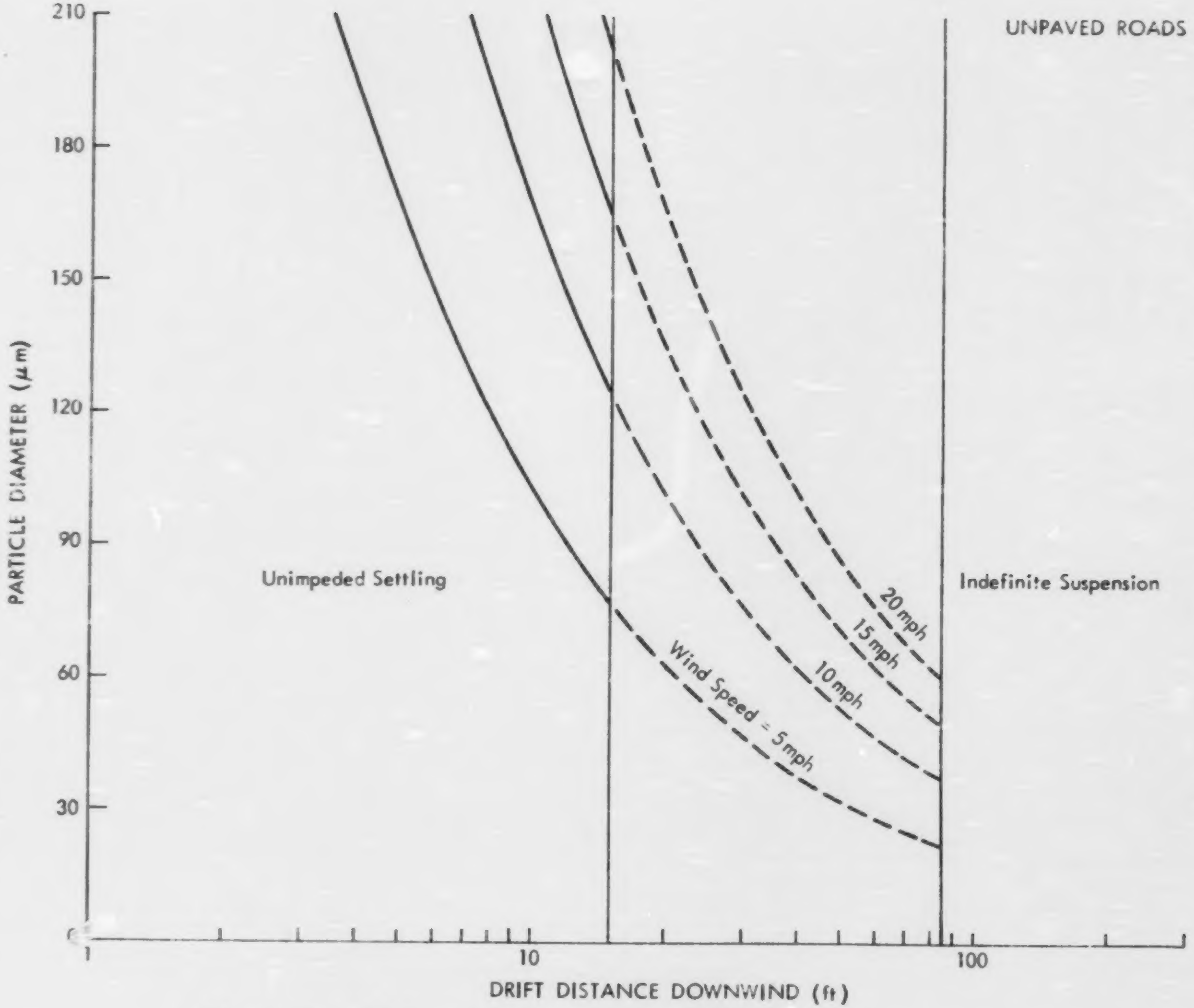

Figure 9. Drift potential of road emissions.

It can be shown that Hoover's data[8] on the deposition near a gravel road is consistent with Figure 9. Assuming that all wind directions were equally likely over the 21-day test period (which means that the average drift distance is 1.57 times the perpendicular distance from the road), particles larger than 75 μm settled within a drift distance of 75 ft. The normal average wind speed for the test period was 9 mph.[24]

Lundgren's study[15] of the capture efficiency of a standard high-volume sampler is also useful to the interpretation of particle size spectra associated with the exposure measurements. He found that for wind speeds in the 3-10-mph range, the suspended dust mass fraction not collected by the high-volume samplers (operating at 55 cfm) was approximately equal to the total mass fraction greater than 60 μm diameter, for a particle density of 1-1.5 g/cm^3.

The effective cut-off diameter for capture of dust by a standard high-volume sampler (or a high-volume cascade impactor operated within a standard enclosure) is taken to be 30 μm for a particle density of 2.5 g/cm^3. This value is based on (1) Lundgren's result, (2) the settling characteristics of road dust particles and (3) the observed ratios of total high-volume concentration to isokinetic profiler concentration.

In the determination of emission factors for unpaved roads, dust which settled out before reaching the exposure profiler (within 20-30 ft of drift distance from the downwind edge of the road) was not included in the emission factor; these particles are larger than 100 μm for winds exceeding 10 mph.

The equations for calculation of the emission factors for three particle size ranges (< 2 μm, 2-30 μm, > 30 μm) are as follows:

1. For particles less than 2 μm in diameter:

$$e_{<2} = ER_6F_{<2} \quad ,$$

where $e_{<2}$ = mass of dust emissions less than 2 μm in diameter per vehicle-mile of travel (pounds per vehicle-mile)
E = integrated exposure measurement (pounds per vehicle mile)
R_6 = ratio of the dust concentration measured by the standard high-volume sampler to the concentration measured by the isokinetic profiler at 6-ft height
$F_{<2}$ = fraction of the particles less than 2 μm in diameter, measured by high-volume cascade impaction.

2. For particles with diameters between 2 and 30 μm:

$$e_{2-30} = ER_6(1 - F_{<2}) \quad ,$$

where e_{2-30} = mass of dust emissions with diameters between 2 and 30 μm per vehicle-mile of travel (pounds per vehicle-mile)

and the other symbols are defined above.

3. For particles greater than 30 μm in diameter, but excluding particles which settled out over the first 20-30 ft of drift distance:

$$e_{>30} = E(1 - R_6) \quad ,$$

where $e_{>30}$ = mass of dust emissions greater than 30 μm in diameter per vehicle-mile of travel.

Table 9 presents the calculated emission factors.

CORRECTION PARAMETERS

Atmospheric dust emissions from unpaved roads depend on the following local parameters:

1. Average vehicle speed,
2. Vehicle mix,
3. Surface texture, and
4. Surface moisture.

Each of these factors is discussed below.

Average Vehicle Speed

The test results reported above indicate the total dust emissions from unpaved roads increase in proportion to the average vehicle speed, in the speed range of 30 to 40 mph. As shown in Figure 10, this dependence is corroborated by the results of Duwamish Valley study.[9] Sehmel's data on the resuspension of tracer dust from asphalt roads[10] indicates that the linear dependence extends up to 50 mph. Below 30 mph, however, both Duwamish Valley study and Sehmel's measurements indicate that emissions increase in proportion to the square of the vehicle speed.

Since the typical speed range on unpaved roads is 30-50 mph, the linear dependence of dust emissions on vehicle speed was used in developing the correction factor.

Table 9. CALCULATED EMISSION FACTORS (Unpaved Roads)

Run	Site	Integrated Exposure (lb/vehicle-mile)	Ratio Hi-Vol Catch: Profiler Catch	Fraction of Hi-Vol Catch < 2 µ	Emission Factors (lb/vehicle-mile)[a] d > 30 µm	2 < d < 30 µm	d < 2 µm	Total
1	R1	10.0	0.60	0.45[b]	4.0 (40%)	3.3 (33%)	2.7 (27%)	10.0
2	R2	10.3	0.66	0.45[b]	3.5 (34%)	3.7 (36%)	3.1 (30%)	10.3
3	R2	13.9	0.57	0.45[b]	6.0 (43%)	4.3 (31%)	3.6 (26%)	13.9
8	R3	16.3	0.50	0.46[b]	8.2 (50%)	4.4 (27%)	3.7 (23%)	16.3
10	R3	6.0	0.65	0.46	2.1 (35%)	2.1 (35%)	1.8 (30%)	6.0
13	R4	55.9	0.57	0.41	24.0 (43%)	18.8 (34%)	13.1 (23%)	55.9

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[a] d = particle diameter

[b] Estimated value

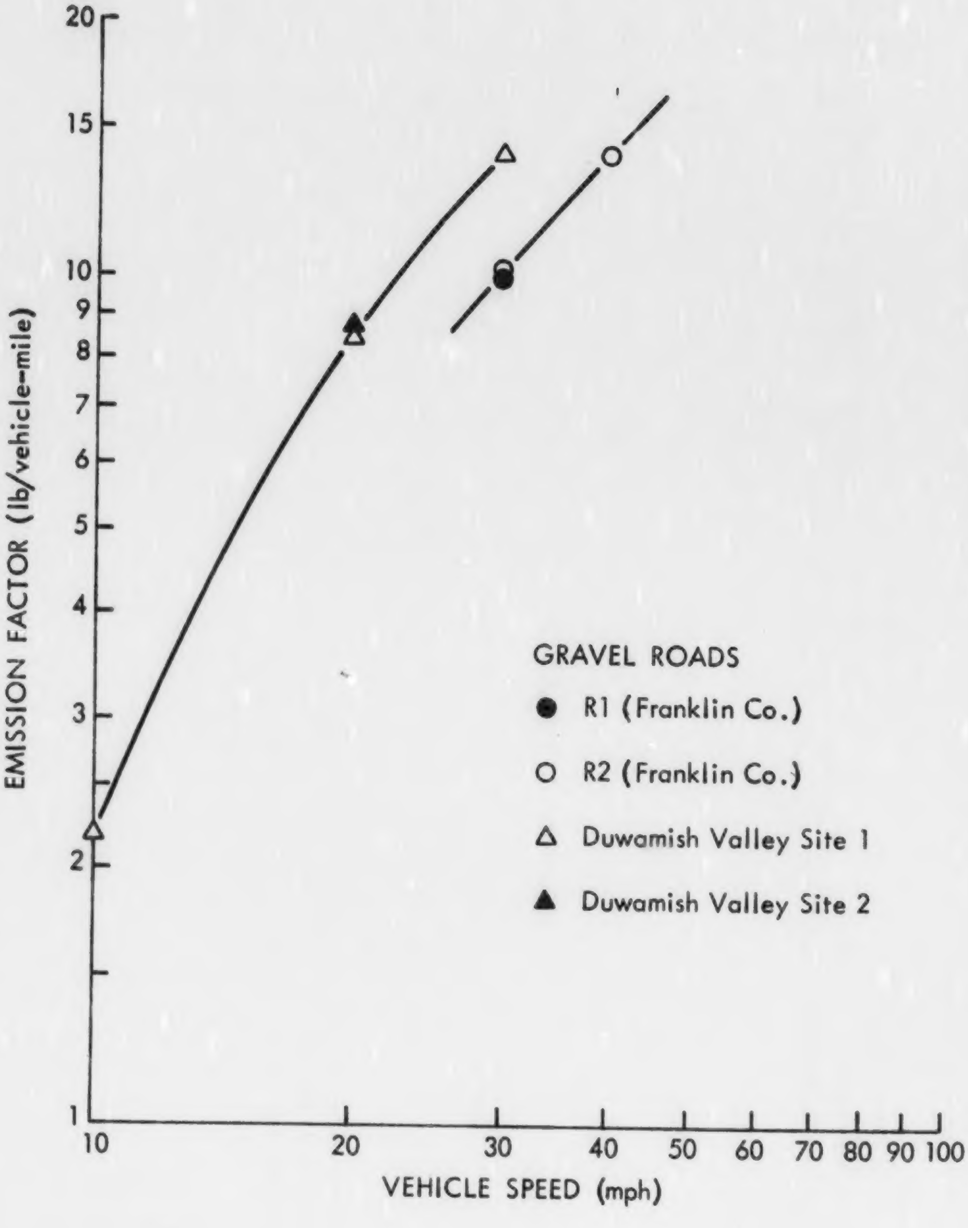

Figure 10. Effect of vehicle speed on gravel road emissions.

Vehicle Mix

Based on the limited data presented in this report, a vehicle traveling an unpaved road generates dust in proportion to the number of its wheels. The emission factors presented above are based on equivalent four-wheeled vehicles. For roads with a significant volume of heavy-duty trucks or other vehicles, the traffic volume should be adjusted to the equivalent volume of four-wheeled vehicles.

Surface Texture

Since the dust emissions which drift more than a few feet from an unpaved road are smaller than 75 μ in diameter, (i.e., defined as silt particles), a linear dependence of emission on silt content of the road surface material may be assumed. The average silt content of the loose material on gravel roads was found to be 12.5%.

The amount of surface fines on an unpaved road is normally close to an equilibrium value. The fines which are injected into the atmosphere by vehicular traffic, are replaced in the same process by new fines which are generated by abrasion of surface material. As was the case for Site R3 in Morton County this equilibrium can be upset by a windstorm or other severe phenomenon, and for a time emissions are reduced.

Surface Moisture

Unpaved roads have a hard, nonporous surface which dries quickly after a rainfall. The temporary reduction in emissions because of rainfall is accounted for by neglecting emissions on "wet" days, i.e., days with more than 0.01 in. of rainfall.

CORRECTED EMISSION FACTOR

The correction parameters discussed above have been incorporated into a single mathematical expression for the amount of dust generated per vehicle-mile of travel. The equation for estimating the total amount of road dust emissions with drift potential greater than 25 ft, i.e., particles smaller than 100 μm in diameter, is as follows:

$$e_{(roads)} = 0.81\ s\ (S/30) \quad ,$$

where e = emission factor (pounds per vehicle-mile)
s = silt content of road surface material (percent)
S = average vehicle speed (miles per hour).

As shown in Table 10, the precision of this equation in predicting the results of the emission tests of unpaved roads is ± 10%.

The silt content (i.e., particles smaller than 75 µm in diameter) of the road surface is determined by measuring the amount of loose (dry) surface dust which passes a 200 mesh screen. The silt content of gravel roads is approximately 12%.

The above equation applies to "dry" days. Emissions are assumed to be negligible on days with rainfall exceeding 0.01 in.

The test results presented above indicate that, on the average, dust emissions from unpaved roads have the following particle size characteristics:

Particle Diameter	Weight Percent
< 2 µm	25
2 µm - 30 µm	35
30 µm - 100 µm	40

Table 10. ESTIMATED VS ACTUAL EMISSIONS (Unpaved Roads)

Run	Site	Vehicle Speed (mph)	Percent Silt	Emission Factor (lb/vehicle-mile) Estimated	Emission Factor (lb/vehicle-mile) Actual	Percent Difference
1	R1	30	12	9.7	10.0	-3
2	R2	30	13	10.5	10.3	2
3	R2	40	13	14.0	13.9	1
8	R3	30	20[a]	16.2	16.3	-1
10	R3	40	5[a]	5.4	6.0	-10
13	R4	30	68	55.1	55.9	-1

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a/ Estimated value

CHAPTER 5

AGRICULTURAL TILLING EMISSIONS

SAMPLING SITE DESCRIPTION

Morton and Wallace counties in Kansas were selected for the study of atmospheric dust emissions from agricultural tilling. Located in extreme southwest and west-central Kansas, respectively, both counties are in the dry, windy area of the Great Plains referred to as the "dust bowl," where problems of windblown dust are severe. The climatic potential for wind erosion in the dust bowl area is illustrated in Figure 11, which presents the distribution of annual average values of the climatic factor used in the wind erosion equation.[25]

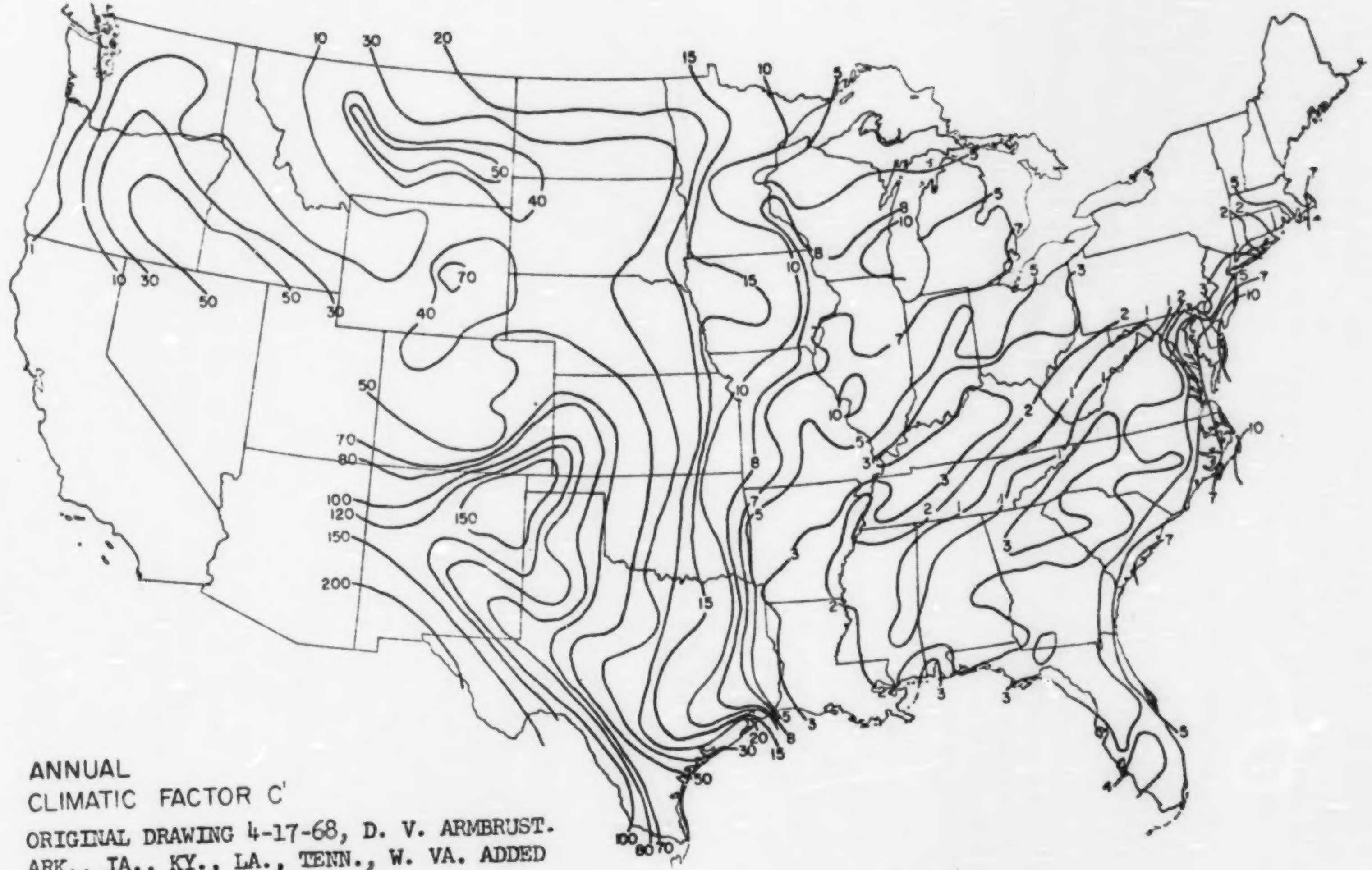
Detailed descriptions of the characteristics of the individual test sites are given in the following paragraphs.

Morton County, Kansas

Morton County is located in the southwest corner of Kansas, near the center of the dust bowl area of the Great Plains. The annual rainfall in the county averages 16 in. and the average wind speed is 14 mph with prevailing winds from the southwest.

Morton County is a part of the southern High Plains section of the Great Plains physiographic province. About 85% of the county consists of upland plains and rolling to hilly sandy land and the rest is stream flood plains and intermediate slopes. Large areas on the upland are comparatively flat and featureless. In detail, however, most parts of the flat upland are more or less uneven and consist of broad, gentle swells or hills and shallow depressions.

The Cimarron River passes through the central part of the county. In this county it is an intermittent stream that flows only when there is a large amount of rainfall upstream.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ANNUAL
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ORIGINAL DRAWING 4-17-68, D. V. ARMBRUST.
ARK., IA., KY., LA., TENN., W. VA. ADDED
11-24-71, N. P. WOODRUFF.

Figure 11. Climatic factor used in wind erosion equation.

About 50% of the county is drained by the Cimarron River and its tributaries; the rest has no exterior drainage. Rain that falls on flat upland and sandhills drains into temporary ponds or small, shallow lakes, where it evaporates or percolates downward.

The elevation of the upland ranges from about 3,700 ft above sea level in the southwestern part of the county to 3,150 ft on the eastern county line. In general, the county slopes to the northeast and east about 15 ft/mile. The Cimarron River is more than 100 ft below the upland areas.

A soil survey of Morton County is complete and fully documented,[26] and it is tied in with aerial photographs. The two major soil associations are Richfield/Ulysses and Dalhart/Richfield which cover 58 and 17% of the county, respectively, and comprise the agricultural soils which are cultivated to produce crops.

The Richfield/Ulysses association occurs in two nearly level to gently sloping areas of the uplands, mostly in the northern half of the county. It is composed mainly of soils with a loamy surface layer. Most of this association is used for crops, principally grain sorghum and wheat, which are often grown on a crop-fallow system. Most of the irrigation in the county is done on soils of this association.

The Dalhart/Richfield association occurs south of the Cimarron River and is composed of soils with a sandy surface layer. Most of this association is used to produce crops. Sorghum is the main crop, but wheat is grown on a small portion of the acreage.

Two individual sites in Morton County were selected for the study of atmospheric emissions from agricultural tilling. Site A1, located in the south-central part of the county, was a section of fallow acreage with a surface of fine sandy loam; the terrain was level and there was little vegetative cover. Site A2, located in the west-central part of the county, was a section of fallow acreage with a surface of silt loam. Additional details of the site characteristics are given in Table 11.

Wallace County, Kansas

Wallace County is situated on the western-most tier of Kansas counties about one-third of the way downstate, in the dust bowl area of the Great Plains. The annual rainfall in the county averages 22 in. and the average wind speed is 14 mph with prevailing winds from the southwest.

Table 11. AGRICULTURAL SITE CHARACTERISTICS

Site	Location	Soil Type	Slope
A1	Morton County: T35S, R41W, Section 8	Dalhart/Richfield fine sandy loam	0-1%
A2	Morton County: T33S, R43W, Section 22	Ulysses/Richfield silt loam	0-1%
A3	Wallace County: T13S, R40W, Section 19	Ulysses/Colby silt loam	1-2%
A4	Wallace County: T13S, R41W, Section 26	Keith/Colby silt loam	Terraced

The soil of Wallace County is derived from three major soil associations: (1) Canyon/Colby (immature and shallow soils on steep slopes) in the north; (2) Keith/Colby in a band from west-central to southeast, and (3) Richfield/Colby in the southwest part of the county. The Keith/Colby and Richfield/Colby associations are chestnut-colored soils developed under prairie vegetation and are representative of a large area of the Great Plains. An extensive soil survey is underway and is being tied to aerial photographs.

The Keith/Colby and Richfield/Colby soils are well suited to cultivation for crop production. The area has traditionally grown a crop of winter wheat every second year in rotation with summer fallow.

Two individual sites in Wallace County were selected for the study of atmospheric emissions from agricultural tilling. Both sites were located in the central portion of the county, just west of Sharon Springs. Site A3 was a section of gently sloping fallow land with light vegetative cover. Site A4 was a terraced section of fallow land with light vegetative cover. The surface soil at both sites was a silt loam. Additional details of the site characteristics are given in Table 11.

FIELD MEASUREMENTS

Field testing of dust emissions from agricultural tilling was conducted at the Morton County sites (A1 and A2) in May and June 1973, and at the Wallace County sites (A3 and A4) in June 1973. The testing of agricultural tilling emissions had to be postponed from dates scheduled in March and April because of adverse weather conditions, as explained below.

The spring of 1973 was one of the wettest in history in the Great Plains. During March and April flooding was widespread and received extensive news coverage. Because fugitive dust emissions are highly dependent on surface moisture, the decision was made not to test under these highly nonrepresentative conditions. As a result, testing was curtailed until mid-May.

Because of persistent wet weather in March and April, the tilling operations in preparation for spring planting were very atypical and were not tested. Instead of the originally scheduled testing of tilling emissions from spring seedbed preparation, testing was conducted on the tilling of fallow ground which was later planted in winter wheat (at the end of the summer).

The tillage implements which were selected for testing were the one-way disk plow and the sweep-type plow. These implements were chosen, with the advice of area agricultural specialists, as representative of implements used in dryland farming in the Great Plains.

Table 12 specifies the kinds and frequencies of field measurements that were conducted during each run. "Composite" samples are made up of single samples taken from several locations in the area; "integrated" samples are those taken at one location for the duration of the run.

Composite samples of soil (8-12 cores) were obtained with a plugging device from randomly selected locations within 100 yards of the exposure profiler. The soil was sampled separately to depths of 4 and 6 in. The soil samples were stored in polyethylene bags and returned to MRI for laboratory determination of texture and moisture content.

At the end of each run, the collected samples of dust emissions were carefully transferred to shipping containers within the MRI instrument van to prevent dust losses. High-volume filters (from the MRI exposure profiler and from standard high-volume units) were placed in individual folders. Dust that collected on the interior surfaces of each exposure probe was rinsed with distilled water into a glass jar. The contents of the deposition samplers and saltation catchers were also rinsed into glass containers. Cascade impactor collection papers were left in place within each impactor unit.

Table 13 presents information on the time of each run, the prevailing meteorological conditions and the tillage implement. The duration of sampling for the exposure profiler was a fraction of the total elapsed test time because the profiler was operated only when the tillage implement was nearby. The other sampling devices were operated continuously during the run.

Table 14 gives the locations (intake height and distance from tillage path) of the various plume sampling devices that were used for each run. The dust particle sizing samplers included Andersen and Sierra high-volume cascade impactors (operated within a standard high-volume enclosure). The drift distance multiplier, given in the last column of the table, takes into account the effect of the angle between the horizontal wind direction and implement path direction, on the plume travel distance.

Table 12. FIELD MEASUREMENTS--AGRICULTURAL TILLING

Test Parameter	Units	Sampling Mode	Measurement Method
1. Meteorology			
a. Wind speed	mph	Continuous	Recording instrument at "background" station; sensors at reference height
b. Wind direction	deg	Continuous	
c. Cloud cover	%	Single	Visual observation
d. Temperature	°F	Single	Sling psychrometer
e. Relative humidity	%	Single	
2. Field Surface			
a. Soil texture	μm	Composite	Hydrometer method
b. Soil moisture content	%	Composite	Weight loss on oven drying
c. Vegetative cover	--	Multiple	Observation (photographs)
3. Tillage Equipment			
a. Type	--	Single	Observation (photographs)
b. Dimensions	ft	Single	Observation (photographs)
c. Translational speed	mph	Multiple	Elapsed time between reference points
d. Number of passes	--	Cumulative	Counting
4. Suspended Dust (downwind unless indicated)			
a. Exposure (vs height)	mg/in^2	Integrated	Isokinetic high-volume filtration (MRI method)
b. Size distribution (by wt.)	μm	Integrated	Cascade impaction
c. Concentration	$\mu g/m^3$	Integrated	High-volume filtration (EPA method[17])
d. Background concentration	$\mu g/m^3$	Integrated	High-volume filtration (EPA method[17])
e. Duration of sampling	min	Cumulative	Timing
5. Large Particle Transport			
a. Deposition (vs distance from source)	lb/ft^2/hr	Integrated	Dustfall buckets (ASTM method[18])
b. Saltation	mg/in^2	Integrated	Saltation catcher

Table 13. EMISSIONS TEST PARAMETERS (Agricultural Tilling)

Run	Site	Date	Time		Duration of Exposure Sampling (min)	Direction of Travel	Ambient Temp. (°F)	Wind Direction/ Speed (12 ft)	Cloud Cover (%)	Pasquill Stability[a]	Tillage Implement		No. of Passes
			Start	Finish							Type	Speed (mph)	
5	A1	24 May 1973	1415	1727	32.5	E-W	74	N/13 mph	0	B	12-ft disk	5-6	15
6	A1	24 May 1973	1818	1958	13.7	E-W	74	N/13 mph	0	D	12-ft disk	5-6	10
7	A1	25 May 1973	0940	1108	24.3	E-W	70	S/12 mph	30	A-B	12-ft disk	5-6	16
9	A2	5 June 1973	1125	1350	31.0	E-W	75	NW/10 mph	5	A	30-ft disk	4	10
11	A3	12 June 1973	0829	1009	25.0	E-W	68	NE/12 mph	80	D	30-ft sweep	6-7	12
12	A3	12 June 1973	1117	1409	22.0	E-W	80	NE/10 mph	80	C	30-ft sweep	7	12
14	A4	13 June 1973	1111	1222	25.0	N-S	70	SE/8 mph	100	C	20-ft disk	5[b]	12

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[a] Pasquill Stability Classes:[19]
A - Extremely unstable
B - Unstable
C - Slightly unstable
D - Neutral
E - Slightly stable
F - Stable to extremely stable

[b] Estimated value

Table 14. DUST EMISSION SAMPLER LOCATIONS (Agricultural Tilling)

		Perpendicular Distance from Downwind Edge of Tillage Path (ft)					
Run	Site	MRI Exposure Profiler[a]	Particle Size Classifier[b] (h = 6 ft)	Deposition Sampler (h = 1 ft)	Saltation Catcher ($1 \le h \le 2.5$ ft)	Standard Hi-Vol Sampler (h = 6 ft)	Drift Distance Multiplier[c]
5	A1	20	20 (AI)	-	20	-	1.0
6	A1	22	22 (SI)	-	22	-	1.0
7	A1	20	20 (AC)	-	20	-	1.0
9	A2	20	-	20	20	20	1.4
11	A3	20	20 (AI)	20	20	-	1.4
12	A3	20	20 (AI)	-	20	-	1.4
14	A4	22	22 (AI)	-	22	-	1.4

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[a] Sampling heights: h = 3, 5.5, 8, and 10.5 ft above grade.

[b] Sizing device: AI = Andersen impactor
SI = Sierra impactor
AC = Aerotec cyclone

[c] Ratio of drift distance to perpendicular distance.

TEST RESULTS

Dust samples from the field tests were analyzed gravimetrically in the laboratory. Filters were conditioned in a controlled temperature-humidity environment prior to weighing. Water rinses from exposure probes, deposition samples and saltation catchers were evaporated on a steam bath in tared beakers, after which the beakers were conditioned and weighed.

The measured dust emissions from the tests of agricultural tilling are shown in Table 15. The dust quantities are the amounts generated per mile of 12-ft tilling cut. This normalization basis has been chosen for comparison with unpaved road emissions.*

The total dust emissions for a given run are the sum of the integrated exposure (above the background exposure) and the amount of deposition between the edge of the road and the downwind location of the exposure profiler.

The suspended dust measurements used to compute the integrated exposure are presented in Table 16. Point values of exposure are converted to concentration. The concentration measured by the standard high-volume unit, which was positioned to the side of the profiler, is also presented. The exposure profiles are shown in Figure 12.

In general, deposition measurements were not obtained for agricultural tilling because most of the deposition occurs on the tilled land. A deposition measurement was made for Run 11 and the cumulative deposition between the downwind edge of the tillage path and the exposure profiler, was determined by the method described in Chapter 4.

The measurements of dust transport by saltation are shown only for purposes of comparison. Saltation, which is confined to about 30 in. of height, is not considered to be a form of atmospheric emissions. Also it should be noted that the saltation catchers used in this study did not sample below 12 in. above the ground.

Also given in Table 15 is the mass mean diameter of suspended dust particles measured with the Andersen high-volume cascade impactor. The diameter values are aerodynamic measures which treat particles as equivalent spheres with a density of 2.5 g/cm^3. The complete size distributions are shown in Figure 13.

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* A typical roadway lane is 12 ft in width.

Table 15. MEASURED DUST EMISSIONS (Agricultural Tilling)

Run	Site	Background Concentration ($\mu g/m^3$)	Wind Speed (mph)	Plume Travel Time to Profiler (sec)	Unit Dust Catch (lb/mile of 12 ft cut)			Hi-Vol MMD[a] (μm)
					Saltation	Deposition	Integrated Exposure	
5	A1	44.5	13	1.0	1.8	-	81.4	2.3
6	A1	44.5	13	1.0	1.9	-	75.4	-
7	A1	-	12	1.1	5.4	-	86.6	-
9	A2	40.6	10	1.9	0.66	-	50.5	-
11	A3	30.7	12	1.6	0.84	11.4	92.4	2.5
12	A3	30.7	10	1.9	0.80	-	124	2.0
14	A4	87.6	8	2.6	1.3	-	114	2.9

---

[a] Mass mean diameter of suspended dust, measured with Andersen high-volume cascade impactor.

Table 16. PLUME SAMPLING DATA (Agricultural Tilling)

Run	Site	Height (ft)	Sampling Rate (cfm)	Concentration (mg/m^3)	Unit Exposure (mg/in.^{2}/equivalent pass)
5	A1	10.5	27.5	2.00	0.804
		8	26.8	3.13	1.23
		6[a]	18.5	8.23	--
		5.5	25.0	10.3	3.77
		3	22.8	21.8	7.27
6	A1	10.5	27.5	2.01	0.537
		8	26.8	7.35	1.92
		6[b]	40.3	5.32	--
		5.5	25.0	14.9	3.60
		3	22.8	34.3	10.8
7	A1	10.5	27.5	0.864	0.256
		8	26.8	4.29	1.24
		5.5	25.0	13.4	3.60
		3	22.8	44.0	10.8
9	A2	10.5	24.1	6.17	1.30
		8	22.8	9.52	1.91
		6[c]	42.6	13.5	--
		5.5	21.3	15.8	2.96
		3	19.2	25.4	4.29
11	A3	10.5	24.3	12.3	1.76
		8	23.2	17.2	2.35
		6[a]	22.0	10.5	--
		5.5	21.5	34.3	4.35
		3	19.2	57.7	6.53
12	A3	10.5	28.5	15.6	2.31
		8	27.0	23.9	3.34
		6[a]	24.0	27.9	--
		5.5	25.3	40.7	5.35
		3	23.0	75.9	9.06
14	A4	10.5	19.8	14.3	2.53
		8	18.5	22.9	3.74
		6[a]	27.0	15.3	--
		5.5	17.0	37.1	5.59
		3	15.2	62.3	8.38

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[a] Andersen impactor.

[b] Sierra impactor.

[c] Standard high-volume sampler.

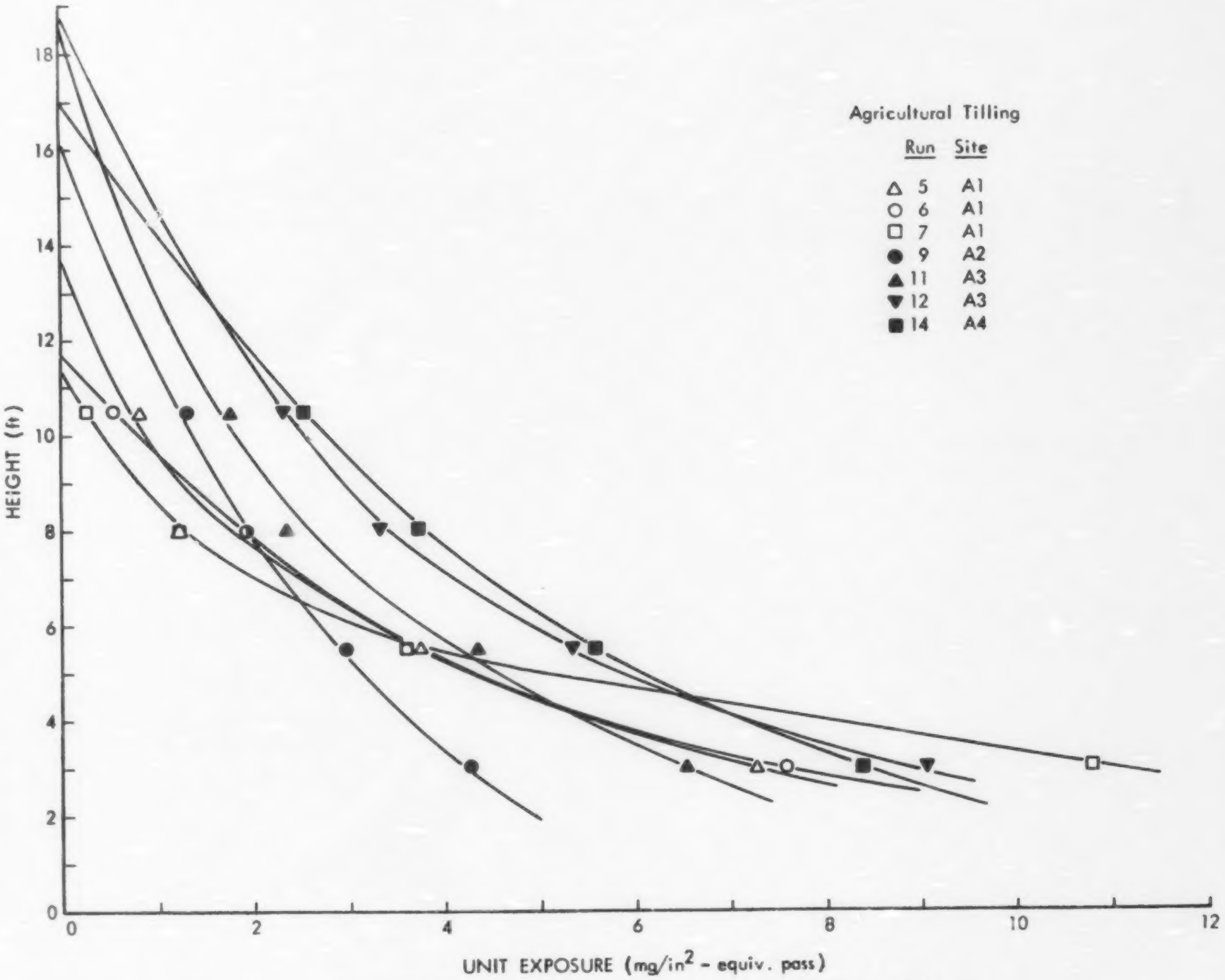

Figure 12. Exposure profiles--agricultural tilling.

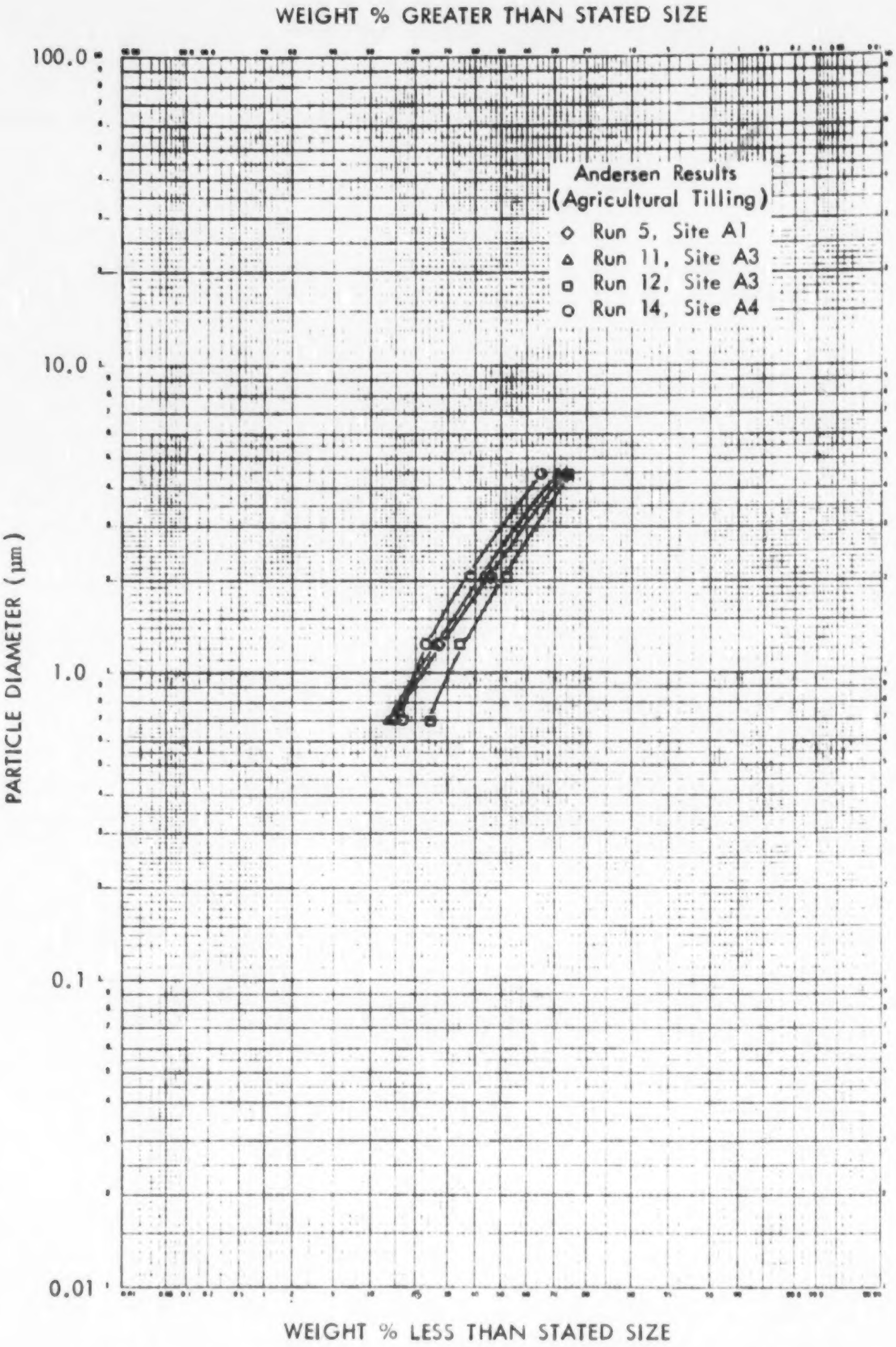

Figure 13. Particle size distributions--agricultural emissions.

Two potentially significant sources of error in the particle size measurements as mentioned in Chapter 4 were:

1. The impactor samples nonisokinetically through the high-volume enclosure openings and collects large particles with low efficiency.

2. Unlike urban aerosol, tillage dust particles are dry and brittle and are subject to bouncing and reentrainment from impaction surfaces. Recent empirical evidence obtained by Sehmel[20/] indicates that this effect is most pronounced for particles larger than 20 µm in diameter.

Both of these factors cause apparent size determinations to be biased in the direction of small diameter. The second factor seemed to be substantial with the slotted impactor (MMD ≈ 1 µ); for this reason, the Sierra measurements were not used.

Table 17 gives the results of the laboratory analyses of the soil samples. Moisture content was determined by weight loss on oven drying and particle size analysis by the Buoyocous hydrometer method[21/] (with sodium hexametaphosphate as a dispersing agent) and by wet sieving.

The significantly higher moisture content of the soil at the 4-6 in. depth in comparison with the 0-4 in. depth, indicates the transfer of moisture from beneath the exposed soil surface to replace moisture lost by atmospheric drying.

As indicated in Table 17, the soil from Site A1 is rich in fine sand and Site A3 has the highest total silt content. The size distributions for the soil samples are plotted in Figure 14.

COMPUTED EMISSION FACTORS

The approach that was used in the development of emission factors for agricultural tilling, is the same as that presented in Chapter 4. Emission factors for three particle size ranges ($d < 2$ µm, $2 \text{ µm} \leq d \leq 30$ µm, $d > 30$ µm) were determined from the integrated exposure measurements, the cascade impactor measurements of particle size and the ratio of high-volume concentration to the isokinetic profiler concentration for a height of 6 ft.

Figure 15 shows the estimated drift distance as a function of the size of the particle injected into the atmosphere and the mean wind speed. For emissions from agricultural tilling, the average height of injection is assumed to be 2 ft. The mean wind speed at 2 ft is related to the speed at the 12-ft reference height by the profile presented in Figure 2. The settling velocity is based on the drag coefficient for spheres[22/] and a particle density of 2.5 g/cm^3.[23/]

Table 17. SOIL PROPERTIES (Agricultural Tilling)

Run	Site	Soil Type	Moisture (%)		Texture, 0-4 in. depth (% by weight)[a]					
			0-4 in. depth	4-6 in. depth	Medium-Coarse Sand (2000-250 µm)	Fine Sand (250-105 µm)	Very Fine Sand (105-50 µm)	Coarse Silt (50-20 µm)	Fine Silt (20-2 µm)	Clay (< 2 µm)
5	A1	Sandy Loam	10.5	10.7	2	35	17	14	12	20
6	A1	Sandy Loam	-	-	2	35	17	14	12	20
7	A1	Sandy Loam	-	-	2	35	17	14	12	20
9	A2	Loam	11.0	-	8	10	22	16	16	28
11	A3	Silt Loam	15.9	19.7	1	1	20	30	18	30
12	A3	Silt Loam	13.4	17.5	1	1	21	30	19	28
14	A4	Silt Loam	12.3	16.5	5	3	18	27	19	28

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[a] Determined by Buoyocous hydrometer method.

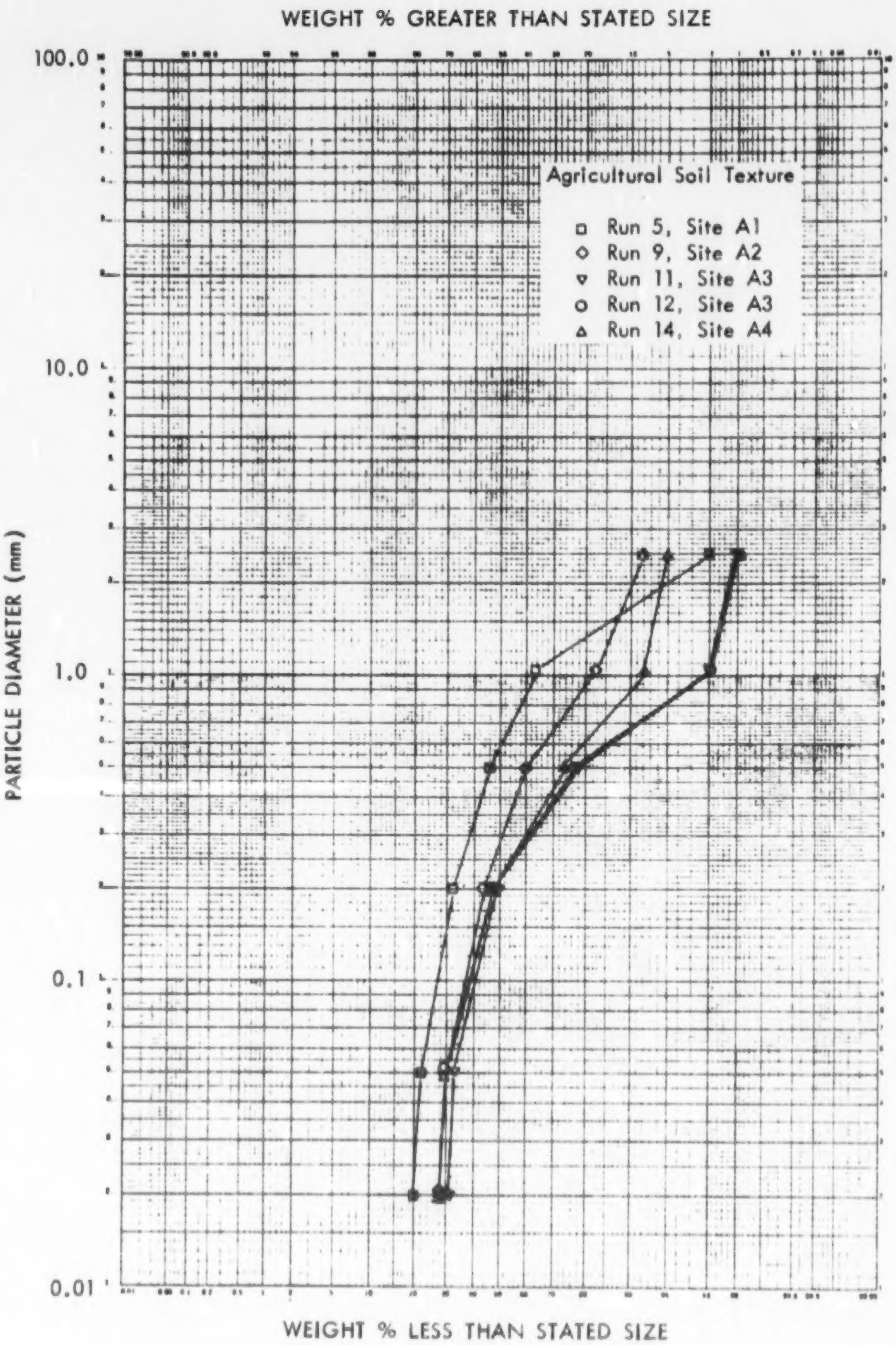

Figure 14. Surface soil texture.

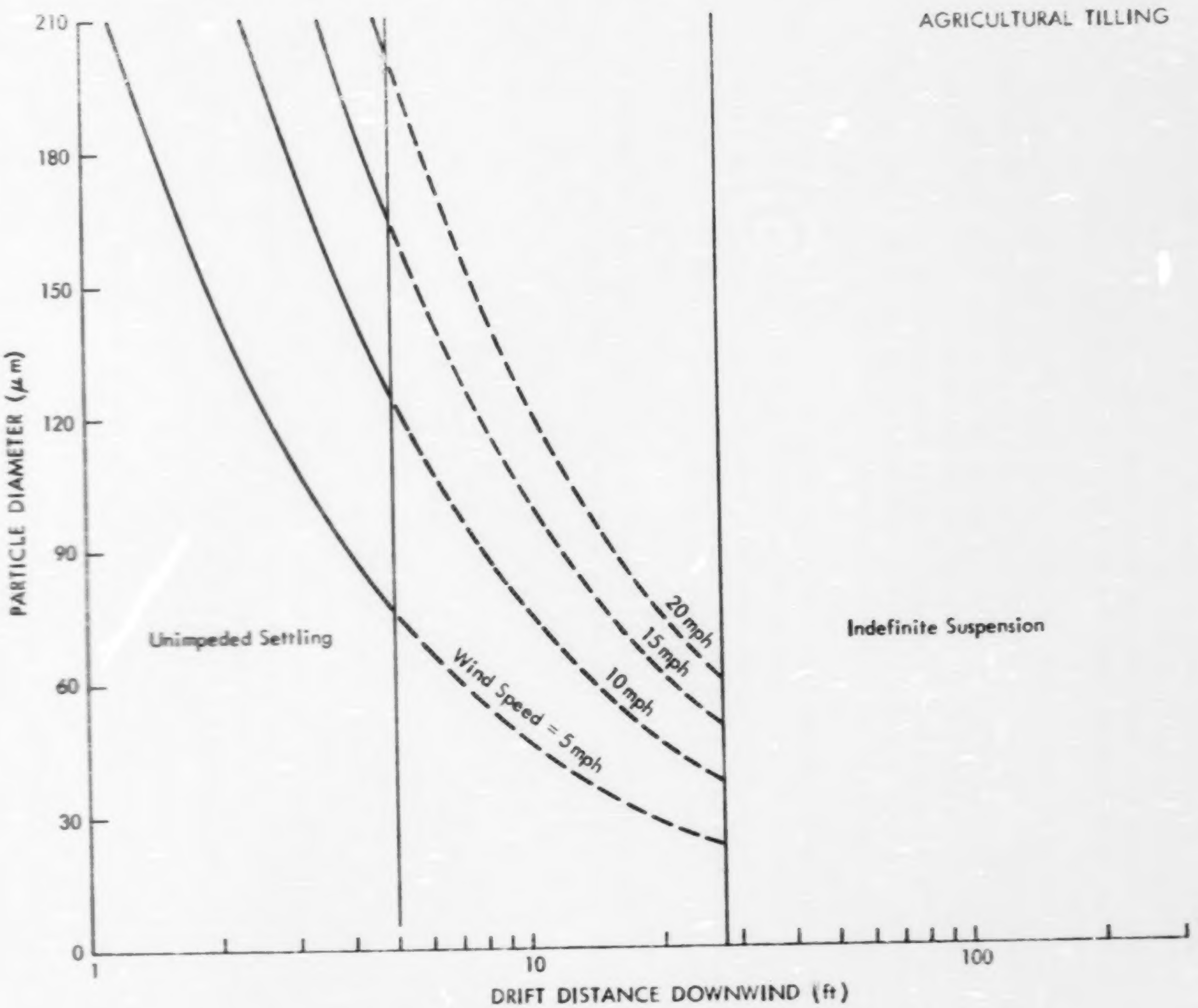

Figure 15. Drift potential of tillage emissions.

The boundaries of the settling and suspension regimes were derived from the Gillette-Blifford criteria[16] using a friction velocity based on a roughness height of 1 cm.[12] As indicated in Figure 15, particles which are not significantly affected by atmospheric turbulence will settle to the ground within a drift distance of 5 ft. Because particles which drift beyond 5 ft are affected by vertical velocity fluctuations, the average drift distance will be greater than the values shown.

The effective cut-off diameter for capture of dust by a standard high-volume sampler (or a high-volume cascade impactor operated within a standard enclosure) is taken to be 30 µm for a particle density of 2.5 g/cm^3. This figure is based on (1) Lundgren's result,[15] (2) the settling characteristics of agricultural dust particles and (3) observed ratios of dust concentration by high-volume measurement to dust concentration by isokinetic profiler measurement.

In the determination of emission factors for agricultural tilling, dust which settled out before reaching the exposure profiler (within 20-30 ft of drift distance from the downwind edge of the tilling path) was not included in the emission factor; these particles are larger than 75 µm in diameter for winds exceeding 10 mph.

The equations for calculation of the emission factors for three particle size ranges (< 2 µm, 2-30 µm, > 30 µm) are as follows:

$$e_{<2} = ER_6F_{<2}$$

$$e_{2-30} = ER_6(1 - F_{<2})$$

$$e_{>30} = E(1 - R_6) \quad ,$$

where e_i = mass of dust emissions with diameter i per acre tilled
E = integrated exposure measurement
R_6 = ratio of dust concentration measured by the standard high-volume sampler to the concentration measured by the isokinetic profiler, at 6 ft height
$F_{<2}$ = fraction of the particles less than 2 µm in diameter, measured by high-volume cascade impaction

The calculated emission factors are presented in Table 18.

CORRECTION PARAMETERS

Atmospheric dust emissions from agricultural tilling exhibit significant dependence on the following variable factors:

Table 18. CALCULATED EMISSION FACTORS (Agricultural Tilling)

Run	Site	Integrated Exposure (lb/mile of 12-ft cut)	Ratio Hi-Vol Catch: Profiler Catch	Fraction of Hi-Vol Catch < 2 microns	Emission Factors (lb/acre)[a/]			
					d > 30 μm	2 < d < 30 μm	d < 2 μm	Total
5	A1	81.4	0.90	0.44	5.6 (10%)	28.2 (50%)	22.1 (40%)	55.9
6	A1	75.4	0.90	0.44[b/]	5.2 (10%)	26.2 (50%)	20.5 (40%)	51.9
7	A1	86.6	0.90	0.44[b/]	6.0 (10%)	30.0 (50%)	23.6 (40%)	59.6
9	A2	60.6	0.90	0.44[b/]	4.2 (10%)	21.0 (50%)	16.4 (40%)	41.6
11	A3	92.4	0.75	0.42	15.9 (25%)	27.7 (44%)	20.0 (31%)	63.6
12	A3	124	0.75	0.50	21.3 (25%)	31.9 (37%)	32.0 (38%)	85.2
14	A4	114	0.75	0.38	19.5 (25%)	36.3 (46%)	22.3 (29%)	78.1

[a/] d = particle diameter
[b/] Estimated value

1. Surface soil texture,
2. Surface soil moisture content, and
3. Implement speed.

Each of these factors is discussed below:

Surface Soil Texture

There is good reason to infer a linear dependence of dust emissions from agricultural tilling on the silt content (i.e., particles between 2 and 50 μ in diameter) of the surface soil. Firstly, dust emissions which drift more than a few feet from a tillage operation are smaller than 50-75 μm in diameter. Secondly, Gillette[23] has found that clay particles (smaller than 2 μm in diameter) remain bound to larger particles during wind erosion because of the relatively large amount of energy required to disaggregate particles in that size range; the same reasoning should apply to dust generated by tilling.

Surface Soil Moisture

Those familiar with agricultural tilling are well aware that dust emissions increase substantially in dry weather. Moisture tends to bind fine dust particles together.

The developers of the Wind Erosion Equation[25] which is used to predict the susceptibility of a given area of land to wind erosion, have found that erosion is inversely proportional to the square of the moisture content of the surface soil. They have adopted Thornthwaite's precipitation-evaporation index[27] as a useful approximate measure of average soil moisture.

The inverse square dependence of dust emissions from agricultural tilling on the moisture content of the surface soil (0-4 in. depth) was demonstrated on a very limited basis at Site R3 in Wallace County, Kansas. Test 11 was conducted in the morning and Test 12 in the early afternoon of the same day; the measured increase in emissions from the same tillage tool was approximately inversely proportional to the square of the decrease in soil moisture.

Implement Speed

Dust emissions from agricultural tilling are dependent on the rate at which mechanical energy is consumed by working the soil. Since tillage implements are designed to operate over a narrow speed range, a linear dependence of emissions on implement speed may be assumed. As a practical matter, data on implement speed is not recorded and emission estimates must be based on the average implement speed.

CORRECTED EMISSION FACTOR

The correction parameters discussed above have been incorporated into a single mathematical expression for the amount of dust generated per acre of land tilled.

The equation for estimating the total amount of tillage dust emissions with drift potential greater than 25 ft, i.e., particles smaller than 75 μm in diameter, is as follows:

$$e_{(tilling)} = \frac{1.4\ s\ (S/5.5)}{(PE/50)^2}$$

where e = emission factor (pounds per acre)
s = silt content of surface soil (percent)
S = implement speed (miles per hour)
PE = Thornthwaite's precipitation-evaporation index

As shown in Table 19, the precision of this equation in predicting the results of the emission tests of agricultural tilling is ± 15%.

The soil silt content (i.e., particles between 50 μm and 2 μm in diameter) may be determined by the Buoyocous hydrometer method.[21/] Surface soil samples should be extracted with a plugging device to a depth of 4 in.

The PE index is determined from total annual rainfall and mean annual temperature; rainfall amounts must be corrected for irrigation.

The test results presented above indicate that, on the average, dust emissions from agricultural tilling have the following particle size characteristics:

Particle Diameter	Weight Percent
< 2 μm	35
2 μm - 30 μm	45
> 30 μm	20

Table 19. ESTIMATED VS ACTUAL EMISSIONS
(Agricultural Tilling)

			Soil Properties[a]			Emission Factor (lb/acre)		
Run	Site	Implement Speed (mph)	Percent Silt	Moisture (% by weight)	Equivalent PE[b]	Estimated	Actual	Percent Difference
5	A1	5.5	26	10.5	40	57	56	2
6	A1	5.5	26	10.5	40	57	52	9
7	A1	5.5	26	10.5	40	57	60	-5
9	A2	4	32	11.0	41	49	42	16
11	A3	6.5	48	15.9	59	56	64	-12
12	A3	7	49	13.4	50	87	85	2
14	A4	5	46	12.3	46	70	78	-10

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[a] 0-4 in. depth.

[b] Precipitation-evaporation index, adjusted to soil moisture.

CHAPTER 6

AGGREGATE STORAGE PILE EMISSIONS

This chapter presents the results of two separate emission testing studies which were conducted to characterize dust emissions from aggregate storage piles. The first sampling program was designed to quantify total dust emissions from the various constituent sources associated with a representative aggregate storage operation. The second study had as its purpose the quantification of emissions from a specific storage transfer operation--aggregate loadout.

TOTAL EMISSIONS FROM AGGREGATE STORAGE OPERATIONS

Sampling Site Description

The Dravo Corporation sand and gravel pit located at Camp Dennison, Ohio (just east of Cincinnati), was selected for testing of dust emissions from aggregate storage piles. A survey of this pit and processing area indicated that its stockpile operations were representative of those at many aggregate quarrying operations of medium and large size.

The Dravo sand and gravel pit at Camp Dennison is situated in the Little Miami River Valley about 7 miles northeast of the point where it meets with the Ohio River Valley. Prevailing winds in this area during the spring and early summer, reinforced by channeling in the river valley, are from the southwest and south.

The Camp Dennison pit produces about 800,000 tons of aggregate annually. The operation is year-round, with production rates changing seasonally with demand for aggregate from local construction projects. For most of the year, excavation, processing, and loading are on a 5-day week, 8-hr day schedule. During the June and July sampling period, the operation was at its peak annual level and was active 5-1/2 days a week, 10 to 12 hr a day.

The gravel pits and stockpiles, as shown in Figure 16, are adjacent to each other. However, they are separated by 40 to 70 ft vertically--the distance from the floor of the pit to the grade level in the processing and storage areas. This separation effectively eliminates the impact of dust emissions from quarrying on the storage area.

The active crushing and screening equipment and loading hoppers are north of the stockpile cluster. The crushing and screening plant shown in Figure 16 as being located in the storage area is not currently in use and was not operated during the sampling period.

The storage area covers approximately 17 acres. There were 15 stockpiles in this area at the time of the field study, ranging in height from 5 to 30 ft. The average height, weighted on the basis of exposed surface area, was 23 ft (7.0 m). The total estimated weight of the aggregate in storage was 50,000 tons, and the approximate total surface area of the 15 piles was 96,000 ft^2 (9,000 m^2).

All stockpiled stone and gravel has been washed and screened, but none has been crushed. Stockpiled sand has been dredged and put into storage without washing or screening. Material processed through the crusher is loaded directly for shipment.

By comparing the amount of material in storage to the annual production rates or daily rates of movement into and out of storage, it is obvious that the stockpiles have a high turnover and that there is significant activity in the storage area on a daily basis. This activity in the storage area affects the rate of dust generation. In other words, dust in aggregate storage areas is produced not just by wind erosion on exposed surfaces, but also by vehicle movement between piles and by disturbances of the aggregate in moving it into and out of piles.

Field Measurements

Field testing of dust emissions from aggregate storage piles at the Camp Dennison site was conducted during a 1-month period beginning 9 June 1973. The test program consisted of 11 24-hr runs and eight 12-hr runs. Table 20 specifies the kinds and frequencies of field measurements that were performed during each run.

Because of the diffuse and variable nature of the source, conventional high-volume samplers with wind direction activators were used to measure dust emissions. A 180-degree sector of sampling was employed, so that any wind with a southerly component activated all the samplers. This effected the isolation of the storage area from the various processing and truck traffic emissions to the north of the storage area and from the pit operations.

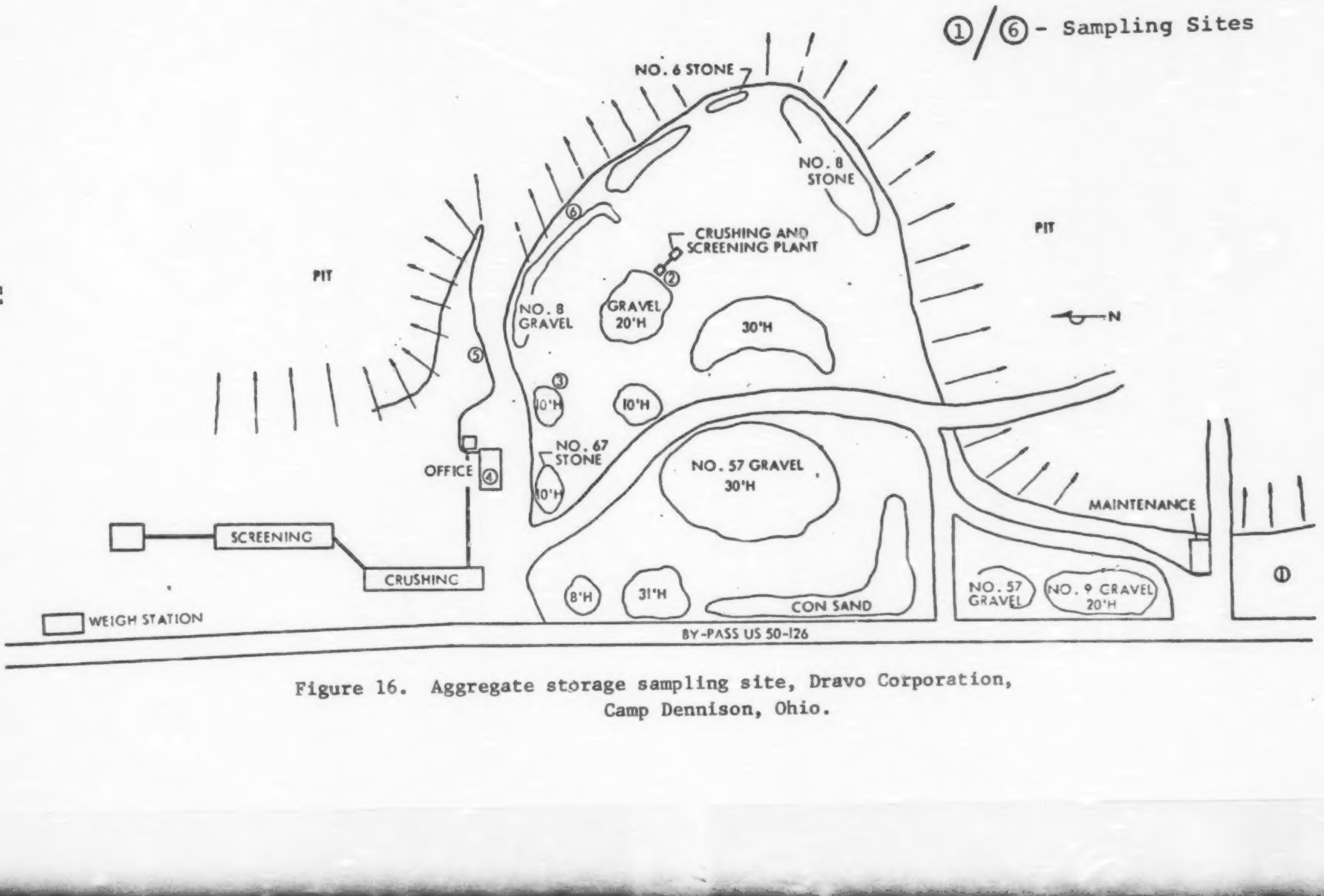
①/⑥ - Sampling Sites
NO. 6 STONE
NO. 8 STONE
PIT
CRUSHING AND SCREENING PLANT
②
⑥
PIT
NO. 8 GRAVEL
GRAVEL 20'H
30'H
N
⑤
③
10'H
10'H
NO. 67 STONE
10'H
OFFICE
④
NO. 57 GRAVEL 30'H
MAINTENANCE
①
SCREENING
CRUSHING
8'H
31'H
CON SAND
NO. 57 GRAVEL
NO. 9 CRAVEL 20'H
WEIGH STATION
BY-PASS US 50-126

Figure 16. Aggregate storage sampling site, Dravo Corporation, Camp Dennison, Ohio.

Table 20. FIELD MEASUREMENTS--AGGREGATE STORAGE PILES

Test Parameter	Units	Sampling Mode	Measurement Method
1. Meteorology			
a. Wind speed	mph	Continuous	Recording instrument on site
b. Wind direction	deg	Continuous	Recording instrument on site
c. Cloud cover	%	Multiple	Hourly readings at Lunken Field
d. Temperature	°F	Multiple	Hourly readings at Lunken Field
e. Rainfall	in.	Cumulative	Daily readings at Lunken Field
2. Aggregate			
a. Size	mm	Single	NCSA standard ranges
b. Pile configuration	--	Single	Observation
3. Suspended Dust			
a. Concentration (vs location)	$\mu g/m^3$	Integrated	High-volume filtration w/directional control
b. Background	$\mu g/m^3$	Integrated	High-volume filtration w/directional control
c. Size distribution (by wt.)	µm	Integrated	Cascade impaction
d. Duration of sampling	min	Cumulative	High-volume time meters
4. Operations Log (only for weekday samples)			
a. Material loaded	tons	Cumulative	Operator's records and estimates
b. Material excavated	tons	Cumulative	Operator's records and estimates
c. Material sized	tons	Cumulative	Operator's records and estimates

A series of five directional high-volume samplers were installed at representative locations immediately downwind from storage piles holding different sizes of aggregate. Locations of the high-volumes are shown in Figure 16.

The samplers were placed at various heights above grade from 3 ft to 20 ft. The assumptions were made that, during periods with winds blowing out of a southerly direction:

1. Particulates were emitted parallel to the wind direction over the entire 980-ft width of the storage area;
2. The emissions occurred from ground level to a height approximated by the average height of the storage piles; and
3. The average particulate concentration at the five downwind sampling stations was representative of the particulate concentration in the assumed rectangular cross section which contained all of the emissions from the stockpile area.

An additional high-volume sampler with the same 180-degree sampling sector was located south of the storage area (at station 1 in Figure 16) to measure the incoming, or background, particulate levels in the airstream. In the data analysis phase, this upwind particulate concentration was deducted from the measured downwind concentration to determine the net contribution from the stockpile area.

The sampling schedule was designed to obtain the maximum possible number of independent samples within a 1-month period. In addition, an effort was made to obtain some of the samples during periods when only wind erosion was causing emissions--12-hr samples from 6:00 PM to 6:00 AM and 24-hr samples from noon Saturday to noon Sunday--for comparison with samples taken during periods when there was movement of the piles and traffic in the stockpile area. The sampling periods are shown in Table 21. All six samplers were operated on the same schedule.

The number of minutes that the directional controls activated the high-volumes were usually almost the same for all six samplers during each sampling period, indicating that wind directions were uniform over the sampling area. The values for running time shown in Table 21 were obtained from time meters attached to the high-volume samplers.

Wind speed and direction data were also measured and recorded at the study site. The weather vane and anemometer at the study site were located on a mast at Station 4, and were about 25 ft above grade with no nearby obstructions. The continuous data have been summarized for 6-hr periods in Table 22. All other meteorological data were obtained from the FAA Weather Station at Lunken Airport, located about 5 miles southwest of the Dravo

Table 21. HIGH-VOLUME SAMPLING DATA
(Sand and Gravel Storage Piles)

Date	Start Time	Test Period (hr)	Sampling Duration (min)					
			Sta. 1	Sta. 2	Sta. 3	Sta. 4	Sta. 5	Sta. 6
6/9/73	1200	24	1130	1140	1082	1074	1165	1064
6/11/73	1800	12	484	403	415	413	423	355
6/12/73	1200	24	1009	1074	1103	1039	1073	1090
6/13/73	1800	12	276	70	73	80	280	62
6/14/73	1200	24	695	424	347	360	661	285
6/16/73	1200	24	1126	1192	1128	1082	1168	378
6/18/73	1800	12	532	340	381	406	619	Void
6/19/73	1200	24	1149	1127	1160	1134	1440	940
6/20/73	1800	12	410	Void	Void	201	719	Void
6/21/73	1200	24	1205	1032	1301	940	1423	1009
6/23/73	1200	24	1087	1011	1440	Void	1352	1024
6/25/73	1800	12	586	578	721	301	719	510
6/26/73	1200	24	1181	1440	1365	1290	240	Void
6/29/73	1800	12	-	-	-	-	-	-
6/30/73	1200	24	1233	1119	1066	1190	982	1032
7/2/73	1800	12	611	613	620	596	378	Void
7/3/73	1800	12	1139	1058	1031	869	1249	1054
7/5/73	1200	24	770	508	420	1311	1280	375
7/6/73	1200	24	1093	734	842	751	1432	706

Table 22. SAMPLING SITE DATA
(Sand and Gravel Storage Piles)

	Wind Speed (mph)				Wind Direction					Material Processed	
Date/Hour	00-0600	06-1200	12-1800	18-2400	00-0600	06-1200	12-1800	18-2400	Precipitation (in.)	Excavated and Sized (tons)	Loaded (tons)
6/9/73			14.5	8.0	SSE		WNW	WNW	0	-	-
6/10/73	2.5	4.5				WSW			0	-	-
6/11/73				6.0				W	0	3830	6461
6/12/73	3.5		15.0	6.0	NNW		W	WSW	0	3850	6461
6/13/73	4.5	5.0		8.0	W	NNW		N	trace	3970	4616
6/14/73	5.0		11.0	7.0	N		ESE	NE	0	4155	3946
6/15/73	3.0	5.5			N	WNW			0	4020	5140
6/16/73			16.0	7.5			W	WSW	0.39	805	-
6/17/73	7.0	10.0			NW	SSW			0.59	-	-
6/18/73				5.5				WSW	0	3600	4555
6/19/73	3.5		17.5	7.5	WSW		SW	SSE	1.96	3645	5334
6/20/73	6.5	12.0		7.5	SSW	WSW		NW	0.03	3855	3059
6/21/73	4.0		9.0	4.0	NW		W	SE	trace	3070	3813
6/22/73	3.5	6.5			WSW	WSW			0	3775	4791
6/23/73			7.0	4.5			N	WSW	0	-	-
6/24/73	4.0	9.0			W	WSW			0	-	-
6/25/73				5.0				SW	0	3385	4854
6/26/73	4.5		25.0	10.5	W		SW	W	0.12	4020	5644
6/27/73	8.0	8.5		9.0	SSW	WSW		WSW	1.37	3375	2655
6/28/73	9.0		19.5	11.0	SW		W	N	trace	1145	2782
6/29/73	4.0	3.5			N	SW			trace	875	-
6/30/73			18.5	7.0			WSW	WSW	0	3670	-
7/1/73	2.5	6.5			N	SSW			0.94	-	-
7/2/73				9.5				WSW	trace	-	-
7/3/73	4.0			8.0	SW			WNW	0.55	-	-
7/4/73	4.0	8.5	9.5		WSW	SSW	NE		0.26	-	-
7/5/73			7.5	4.5			N	NE	0	-	-
7/6/73	2.5	4.5	11.0	6.0	SSE	WSW	SW	SSW	0	-	-
7/7/73	2.5	5.5			N	N			0	-	-

pit in the Little Miami River Valley. Daily rainfall for the sampling period is also presented in Table 22.

As a check of the on-site wind measurements, the 6-hr average wind speeds shown in Table 22 were compared by linear regression analysis with corresponding measurements from Lunken Airport. For the 66 data points considered, the slope of the regression line was 1.11 and the correlation coefficient was 0.86. Thus, the measurements on-site were generally about 11% higher than at the airport, and the two data sets showed a good correlation.

Test Results

The measured background dust concentrations and the net concentrations (background subtracted) at the five downwind stations are shown in Table 23.

In the analysis of the concentration data, several observations were made. First, it was noted that the concentrations at all five stations tended to change together from one sampling period to another, indicating that some external factors such as weather conditions were influencing the emission rate. Also, there was no set pattern in relative concentrations measured at the five stations, i.e., one station did not always have the highest reading and another the lowest. This appeared to show that the points of emission within the storage area were not constant.

The background values recorded at sampling Station 1 were consistent from the standpoint of three different evaluation criteria. First, the concentrations at Station 1 were, with few exceptions, lower than those at the downwind stations. Second, the arithmetic average concentration for the 4-week sampling period was 73.4 $\mu g/m^3$, certainly a reasonable value for this area of the Cincinnati AQCR. Finally, the average concentrations for samples taken during working and nonworking periods were not significantly different--76.1 and 71.7 $\mu g/m^3$, respectively. This indicated that measurements at the upwind station were not influenced by emissions from the sand and gravel operation.

In addition to calculating emission rates for each of the 19 sampling periods, an evaluation of the effects of four different factors on the emission rates was desired. These factors were rainfall, wind speed, type of aggregate, and amount of activity in the piles. Appropriate data on these four variables for periods concurrent with the sampling were required for this evaluation. The sources of these data are described below.

Daily rainfall data at Lunken Airport, shown in Table 22, were used to determine the effect of a wet aggregate surface on emission rates.

Table 23. SUSPENDED DUST CONCENTRATIONS (Sand and Gravel Storage Piles)

			Dust Concentration (μg/m³)						
		Test Period	Background	Net Downwind					
Date	Start Time	(hr)	Sta. 1	Sta. 2	Sta. 3	Sta. 4	Sta. 5	Sta. 6	Average
6/9/73	1200	24	94	8	23	49	13	4	19[a]
6/11/73	1800	12	95	107	152	184	172	76	138
6/12/73	1200	24	60	85	113	252	208	147	161
6/13/73	1800	12	65	215	125	15	0[b]	125	96
6/14/73	1200	24	139	575	134	239	175	259	276
6/16/73	1200	24	75	3	0[b]	0[b]	7	26	7[a]
6/18/73	1800	12	71	21	16	37	42	Void	29
6/19/73	1200	24	49	93	57	105	74	170	100
6/20/73	1800	12	61	Void	Void	48	2	Void	25
6/21/73	1200	24	7	152	140	249	154	108	161
6/23/73	1200	24	67	8	6	Void	9	27	12[a]
6/25/73	1800	12	86	55	19	89	33	210	81
6/26/73	1200	24	58	121	134	50	202	Void	127
6/29/73	1800	12	-	-	-	-	-	-	-
6/30/73	1200	24	61	16	31	0[b]	31	42	24[a]
7/2/73	1800	12	64	20	17	11	71	Void	30
7/3/73	1800	12	50	28	24	28	22	19	24
7/5/73	1200	24	95	231	138	146	150	40	141
7/6/73	1200	24	124	362	170	332	183	241	258
		Average	73	124	76	108	86	107	

---

[a] Weekend sample.

[b] Slightly negative net value; assumed = 0.

Since the high-volume samples ran from noon of one day until noon of the next or from 6:00 PM until 6:00 AM of the next day, a wet sampling period was taken to be one in which there was measurable rainfall on either of the 2 days or the day preceding the first day of the sampling period. If only a trace of precipitation were recorded on one of the sampling days, it was still counted as a wet period. However, trace precipitation on the day preceding sampling did not classify the period as wet.

Since the on-site wind speed data agreed well with corresponding data from Lunken Airport, the on-site readings were used in the analysis. Average wind speeds for periods coincident with the high-volume sampling periods were obtained directly from the already-prepared wind speed summaries.

Dravo personnel at the sand and gravel pit provided information on the grade of aggregate in each storage pile. The grade of gravel or stone is shown in Figure 16 for each pile. Equivalent aggregate size ranges for these grades are presented in Table 24.

The amount of activity in the stockpile area on sampling days could only be obtained indirectly from Dravo's available records. Weights of total material excavated/sized and material loaded onto trucks for shipment were kept for each day, and are presented in Table 22. The difference between these two values provided one estimate of the net weight of material put into or taken out of storage for the day. However, these data proved to be inadequate for comparison with the calculated emission rates for individual sampling periods for the following reasons:

1. The difference between the two values included the weight of material processed and then shipped directly, so was not a good indicator of storage area activity;
2. The time periods for recording material movement were not coincident with sampling periods; and
3. Complete records were not maintained for the entire sampling period.

As an alternate evaluation procedure, the emission rates during working periods were simply compared with those during nonworking periods, when only wind erosion of the piles caused emissions. Since all the samples taken of working periods were 24-hr samples and therefore contained 12 to 14 hr when no activity occurred in the storage area, an emission rate was also calculated for just the portion of these periods when activity actually took place. This was accomplished by determining the equivalent concentration for the 12 working hours that would result in a normal 24-hr concentration when combined with the average 12-hr measurement for nonworking periods.

Table 24. AGGREGATE SIZE RANGES

Grade	Range of Aggregate Sizes (mm)
No. 6	9.5-19.0
No. 8	2.9- 9.5
No. 9	1.3- 4.8
No. 57	4.8-25.4
No. 67	4.8-19.0
No. 304	0.2-25.4
Construction Sand	0.2- 2.0

Source: National Crushed Stone Association

The calculations and graphical analyses employed to determine the effect of the four factors on emission rate are presented in the following section.

Correction Factors

The effect of potentially important correction parameters on dust emissions from aggregate storage piles was assessed by examining the correlation between net downwind dust concentrations and parameter values. The results are described in the following paragraphs.

Rainfall - Using the criteria established above to separate the sampling periods into wet and dry periods, average particulate concentrations were calculated for the two different conditions. On days when the piles were dry, the average concentration caused by the piles (background subtracted) was 141 $\mu g/m^3$, while on rainy days when the piles were wet this average concentration was only 70 $\mu g/m^3$. Wind speeds were approximately the same for the rain and no-rain sampling periods, so the emission rates estimated by the procedure explained in the previous section would be in the same ratio as the high-volume measurements--approximately twice as great during dry periods.

A similar relationship was observed for the background readings measured at Station 1. The average values during wet and dry periods were 59 and 102 $\mu g/m^3$, respectively. This may indicate that relative emissions from wet and dry storage piles are part of a much broader relationship of fugitive dust sources during wet and dry periods. Under this premise, much more data should be available and should be utilized in developing a correction factor for the effect of surface moisture on stockpile emission rates.

There were no extended periods without rain during the month of sampling to investigate whether the emission rates increased proportionately with the time span since the last rainfall.

An additional subdivision of the data into periods when the piles were (a) active and (b) inactive, as shown in Table 25, showed that wet piles did not reduce the emission rate by half for either data subset. However, the wet piles emitted significantly less dust in both cases. Thus, it appears that emission rates may vary by at least a factor of two-fold between wet and dry periods or between wet and dry climates.

Wind Speed - Based on theory, the wind speed should affect high-volume measurements downwind from the storage piles in at least two different ways. First, atmospheric dispersion equations such as those presented in the Workbook of Atmospheric Dispersion Estimates[28/] almost universally

Table 25. AVERAGE HIGH-VOLUME CONCENTRATIONS DURING WET AND DRY SAMPLING PERIODS

	At Five Downwind Sites		At Background Site	
Stockpile Condition	Average Concentration[a] (μg/m^3)	No. of Sampling Periods	Average Concentration (μg/m^3)	No. of Sampling Periods
Wet piles, all sampling periods	70	11	59	12
Wet piles, active	141	3	44	4
Wet piles, inactive	44	8	67	8
Dry piles, all sampling periods	141	6	102	6
Dry piles, active	225	3	119	3
Dry piles, inactive	57	3	85	3

---

a/ Background concentration subtracted.

show that the pollutant concentration downwind from a source is inversely proportional to the average wind speed. These equations assume that the source strength is independent of wind speed. However, for particulate emissions from aggregate storage piles and other fugitive dust sources, it is the force of the wind that at least partially creates the emissions. Thus, some positive relationship also exists between wind speed and particulate concentration.

The high-volume measurements shown in Table 23 were plotted against average wind speeds for corresponding periods in an effort to determine the resultant, or net, function of concentration versus wind speed. The plotted data, shown in Figure 17, indicated no well-defined relationship. In addition to this plot, similar diagrams (not shown) were prepared for each sampling site, with similar results. Also, data subsets such as wet days and dry days were evaluated to find an effect of wind speed on downwind concentrations. Only 12- and 24-hr periods could be studied, since particulate concentrations were not available for any shorter averaging times. The only significant conclusion that could be drawn from these analyses was that high particulate concentrations were not associated with periods of high average wind speed.

Therefore, based on these test results, wind speed did not appear to be a candidate as a correction factor for estimating emission rates from aggregate storage piles.

Aggregate Size - With the available sampling data, the only method of evaluating the effect of aggregate size on emission rate was to compare the average particulate concentration for each site with the size of aggregate in the nearest pile. This procedure was executed, as shown in Figure 18. However, this simple analysis did not indicate any apparent correlation for several reasons:

1. There were only five high-volume sites and therefore only five data points;
2. Each site was actually impacted by several piles, depending on wind direction; and
3. The range of aggregate sizes in the separate piles was quite large (see Table 24), and the size difference between different piles was not distinct.

As previously noted, the data did not demonstrate a continuing pattern in the relative concentrations measured at the five sites, so no "hot spots" of emission within the storage area were suspected.

Also from a theoretical viewpoint, it is doubtful that emission rates are closely related to aggregate size. Fines that are loosely attached to the surface of the aggregate, not the aggregate particles themselves,

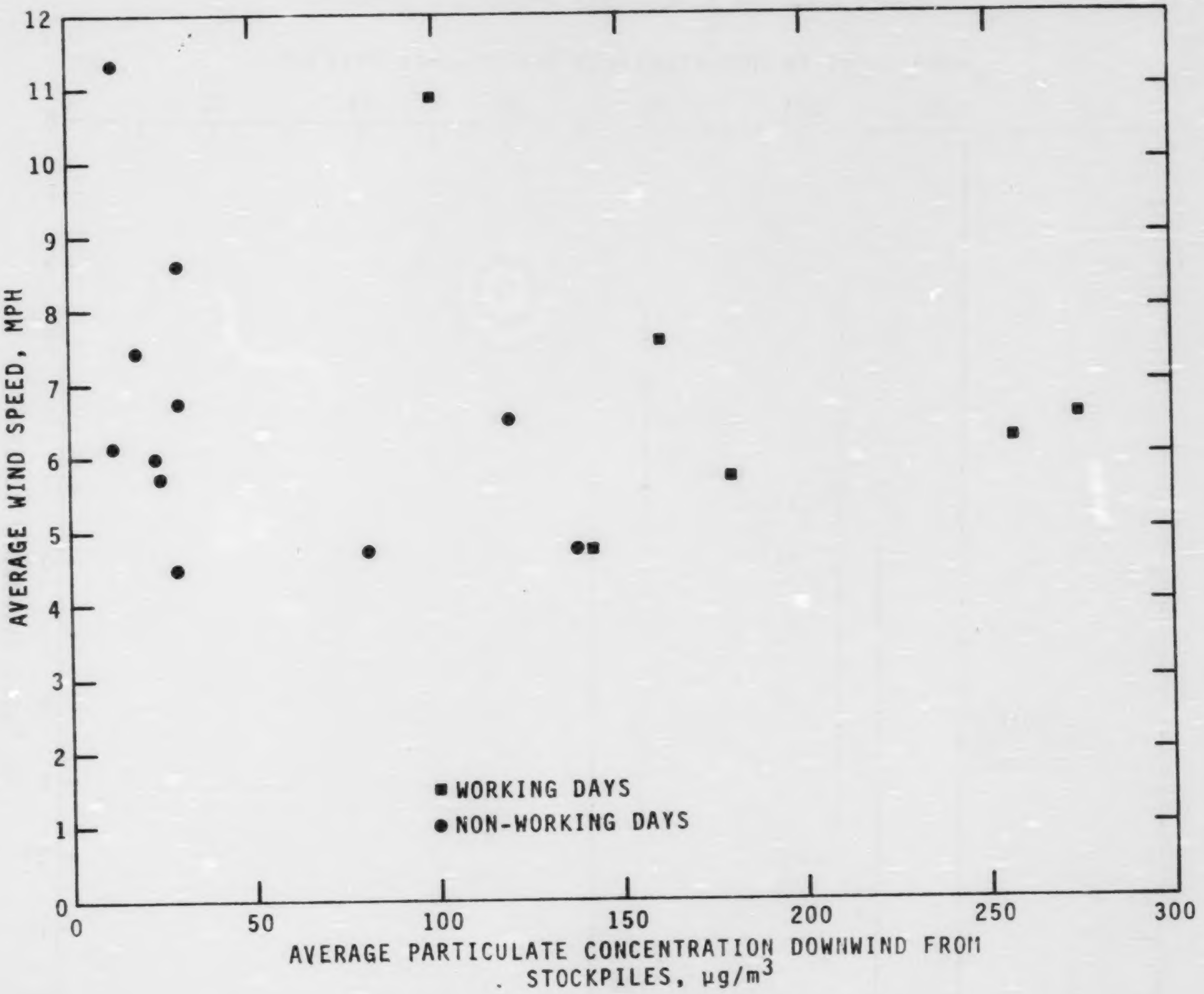

Figure 17. Stockpile emissions vs wind speed.

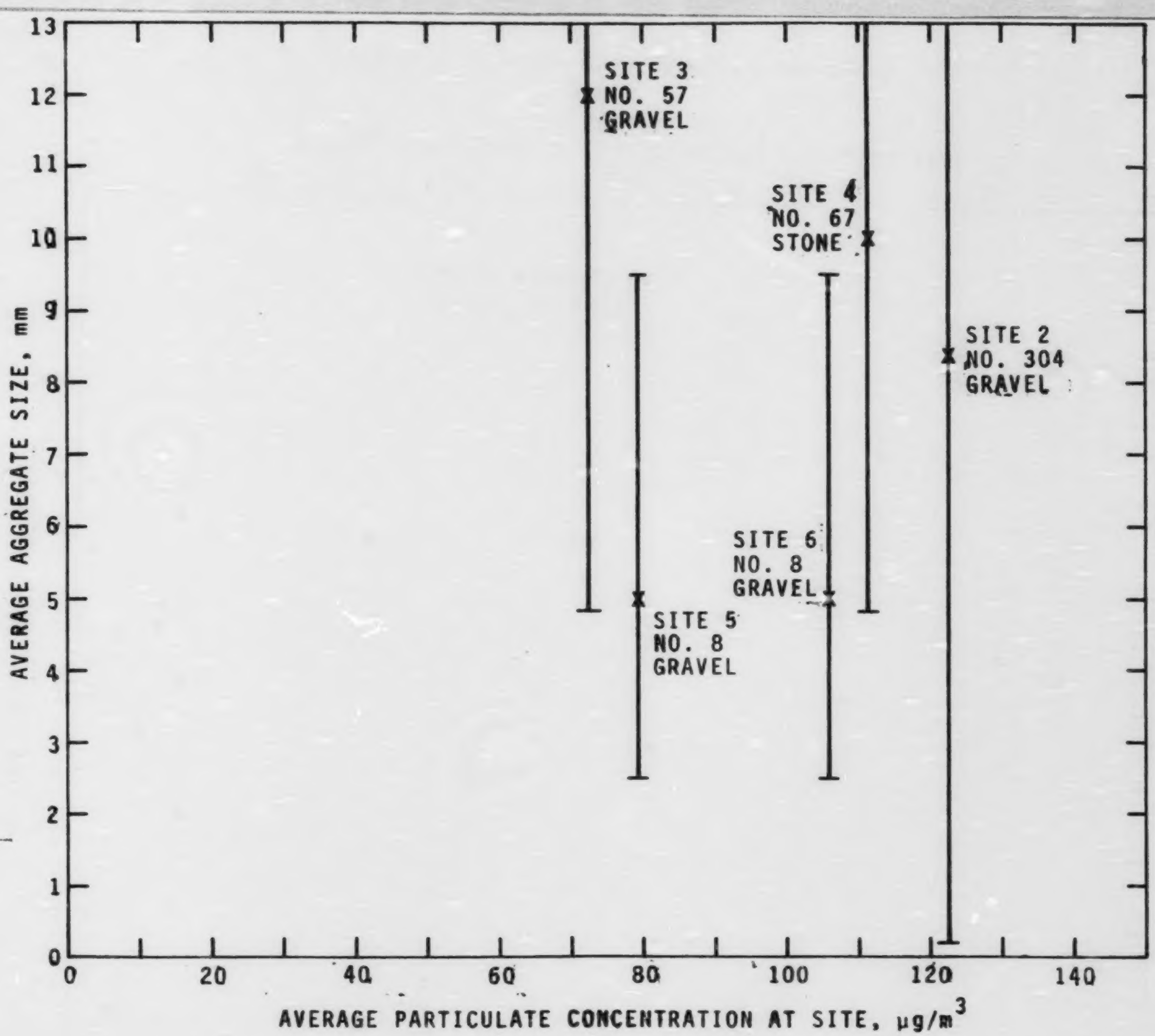

Figure 18. Stockpile emissions vs aggregate size.

become airborne by mechanical entrainment or by wind erosion. Smaller aggregate may contain more fines because of its greater surface area per unit volume or because of additional crushing during its production. On the other hand, rock which is crushed may have more attached fines than sand or gravel which is mined from dry river beds and processed by just screening. No data were found to substantiate or quantify either of these hypotheses.

In summary, aggregate size was not found to be a significant factor in determining the emission rate from an aggregate storage pile.

Activity in the Storage Area - For reasons already explained the data obtained for activity levels in the processing and loading operations were not representative of relative activity in the storage area. If good data for activity in the storage area were available, it is suspected that a relationship could be established. However, such data probably would not be available for other sand and gravel operations either, so would be of very limited use as a correction factor.

Next, a simple analysis was performed comparing measurements taken on working days with those taken overnight or on weekends, when there was no activity in the storage area. The average of all samples from periods with activity was 182.7 $\mu g/m^3$, while the average for all periods with no activity was 47.4 $\mu g/m^3$. Both of these values were after background had been subtracted.

With this significant finding, the readings for working and nonworking periods from each individual site were compared to determine how consistent this observed relationship was. The ratios of working to nonworking periods varied from 2.4/1 at Station 6 up to 5.2/1 at Station 2, as shown in Table 26. At all five stations, significantly higher particulate concentrations were measured when there was activity in the storage area. These results cannot be attributed to differences in meteorology between the 24-hr sampling periods and the 12-hr night samples, because the four 24-hr weekend samples included in the nonworking category had lower readings than the 12-hr night samples.

Therefore, with no exceptions the data pointed to a definite relationship between emission rates from storage piles and activity in the piles, and this relationship should be reflected in the development of an emission factor.

Computed Emission Factors

The general methodology for estimating emission rates from the aggregate storage area has already been described in the preceding section.

Table 26. SAMPLING DATA FOR WORKING AND NONWORKING PERIODS

	Average Hi-Vol Concentration ($\mu g/m^3$)				
Site	Gross for Working Period	Gross for Nonworking Period	Net for Working Period	Net for Nonworking Period	Ratio
1	76.1	71.7	0	0	
2	325.8	119.8	249.7	48.1	5.2
3	201.4	113.0	125.3	41.3	3.0
4	297.3	117.8	221.2	46.1	4.8
5	233.4	108.2	157.3	36.5	4.3
6	236.9	137.8	160.8	66.1	2.4

Briefly, it was assumed that all emissions from the stockpiles passed through an imaginary vertical plane with the dimensions of the width of the storage area by the average height of the piles (300 m by 7 m); that the five samplers located downwind of the piles sampled particulate concentrations representative of average particulate concentrations passing through this vertical cross section; and that the total air volume containing this average concentration could be approximated as the average wind speed times the area of the cross section (2,100 m^2).

Emission rates were calculated for two conditions--active piles and inactive piles. The air volume per day was estimated as 2,100 m^2 times the average wind speed of 3.12 m/sec, or 5.66×10^8 m^3. For average concentrations of 182.7 $\mu g/m^3$ and 47.4 $\mu g/m^3$ for working and nonworking days, the emissions from the study area were calculated to be 103 and 26.8 kg/day, respectively.

Since the 24-hr samples included a time period during which there was no activity, it also appeared reasonable to estimate a shorter-term emission rate for just that portion of the 24 hr during which the activity actually took place. This was accomplished by determining the equivalent concentration for the 12 working hours that would result in a 24-hr average of 182.7 $\mu g/m^3$ when combined with a value of 47.4 $\mu g/m^3$ for the 12 nonworking hours. This value was calculated to be 318.0 $\mu g/m^3$ and resulted in an estimated hourly emission rate of 7.5 kg/hr by using the same methodology as above. This value would be applicable only for short-term emission rates, not for general emission inventory work.

Emission rates from the study area can be used to estimate emission rates from other similar operations only after they have been normalized with an appropriate parameter of the operation's size or production rate. The two parameters which appear to be appropriate for aggregate storage areas, and for which survey data could be obtained, are the acreage of the storage area and the tons of material placed in storage (eliminating the time variable). The calculated emission factors are shown in Table 27.

As specified previously, the above emission factors include the emission contributions from the movement of traffic among the storage piles and from loading and unloading operations, plus wind erosion. They do not include emissions from the mining or processing of the aggregate or from traffic movement in other parts of the plant. It should also be restated that these factors are not universally applicable, but are intended to be representative for storage piles in areas of the country with climatic conditions similar to Cincinnati, Ohio.

As noted in Chapter 2, the only published emission factor for aggregate storage pile losses (in rock handling operations) was reported in

Table 27. CALCULATED EMISSION FACTORS
(Aggregate Storage Piles)

Storage Pile Activity	Emission Factor (lb/acre of storage/day)	Emission Factor (lb/ton placed in storage)
Active[a]	13.2	0.42
Inactive (wind erosion)	3.5	0.11
Normal mix[b]	10.4	0.33

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a/ Eight to twelve hours of activity per 24-hr period.
b/ Five active days per week.

the April 1973, edition of Compilation of Air Pollutant Emission Factors[11/] as 10 lb/ton (5 kg/metric ton). This value is approximately 24 times as high as the factor developed in the present study--0.42 lb/ton, for sand and gravel storage piles with daily activity.

EMISSIONS FROM AGGREGATE LOADOUT

Sampling Site Description

Originally a crushed limestone operation in South Kansas City was designated for the study of atmospheric dust emissions from aggregate loadout from storage piles. Although testing was scheduled in August 1973, a period of record-breaking wet weather ensued, lasting through September. Even after 2 weeks of dry weather, the storage piles remained wet just below the surface and emissions were barely visible. (No freshly crushed, dry rock had been stockpiled during this period.)

Because at that time the crushed stone sales season was coming to a close, no further stockpiling was anticipated either at the designated test site or at other area quarries. This made it necessary to shift the test site to a crushed stone user operation which stockpiled freshly crushed rock.

The Royal Asphalt plant in Kansas City, Missouri, was selected for the testing of emissions from aggregate storage loadout operations. Royal Asphalt maintained stockpiles of four sizes or blends of crushed rock.

To avoid possible interference with normal plant operations and to better control test conditions, testing was scheduled for a weekend. A truck and high-loader were reserved for the testing.

Field Measurements

Field testing of dust emissions from storage pile loadout of crushed rock was conducted at the Kansas City site on 17 November 1973. The asphalt plant was not in operation during testing. A high-loader and a dump truck with a load capacity of about 15 tons were rented for this study.

Table 28 specifies the kinds and frequencies of field measurements that were conducted during each run. "Composite" samples denote a mixture of single samples taken from several locations in the area; "integrated" samples are those taken at one location for the duration of the run.

Table 28. FIELD MEASUREMENTS--AGGREGATE LOADOUT

Test Parameter	Units	Sampling Mode	Measurement Method
1. Meteorology			
a. Wind speed	mph	Continuous	Recording instrument at "background" station; sensors at reference height
b. Wind direction	deg	Continuous	
c. Cloud cover	%	Single	Visual observation
d. Temperature	°F	Single	Sling psychrometer
e. Relative humidity	%	Single	Sling psychrometer
2. Aggregate			
a. Size	mm	Composite	Dry sieve analysis
b. Moisture content	%	Composite	Weight loss on oven drying
c. Age	days	Single	Plant records
d. Pile configuration	--	Single	Observation (photographs)
3. Loading Operations			
a. Type of equipment	--	Multiple	Observation (photographs)
b. Load capacities	tons	Multiple	Plant records
c. Number of loads	--	Cumulative	Observation
4. Suspended Dust			
a. Exposure profiles	mg/in^2	Integrated	Isokinetic high-volume filtration (MRI method)
b. Size distribution (by weight)	µm	Integrated	Cascade impaction
c. Concentration	$\mu g/m^3$	Integrated	High-volume filtration
d. Background concentration	$\mu g/m^3$	Integrated	(EPA method)
e. Duration of sampling	min	Cumulative	Timing

Composite samples of aggregate (12 scoops) were obtained from various points on the worked area of the pile being loaded. The aggregate samples were sealed in polyethylene bags and returned to MRI for laboratory determination of texture and moisture content.

At the end of each run, the collected samples of dust emissions were carefully transferred to shipping containers within the MRI instrument van, to prevent dust losses. After tapping each grid sampler tip so that dust was dislodged onto the filter, the filters were carefully inserted into glycene envelopes which were, in turn, put into paper envelopes. High-volume filters were folded and placed in individual folders. Cascade impactor collection papers were left in place within the impactor unit.

Table 29 presents information on the time of each run, the prevailing meteorological conditions and the weight of aggregate loaded. The exposure profiler was not operated while the truck was dumping its load, but the other sampling instruments were operated continuously during the run.

Test Results

Dust samples from the field tests were analyzed gravimetrically in the laboratory. Filters were conditioned in a controlled temperature-humidity environment prior to weighing. Water rinses from exposure probes, deposition samplers and saltation catchers were evaporated on a steam bath in tared beakers, after which the beakers were conditioned and weighed.

The measured dust emissions from aggregate storage loadout are presented in Table 30. The dust quantities are the amounts generated per ton of aggregate loaded.

The total dust emissions for a given run are the sum of the integrated exposure (above the background) and the amount of deposition between the back of the truck and the exposure profiler, a distance of 5-6 ft. Since only very large particles, which settle quickly, would not reach the exposure profiler, this fraction of the deposition was not considered as a significant air pollution problem.

The suspended dust measurements used to compute the integrated exposure are presented in Table 31. Point values of exposure are converted to concentration. The concentration measured by the standard high-volume unit, which was positioned to the side of the profiler, is also presented.

Table 29. EMISSIONS TEST PARAMETERS (Crushed Stone Storage Piles)

Run	Time Start	Time Finish	Duration of Sampling Exposure (min)	Ambient Temperature (°F)	Wind Direction/ Speed (12 ft)	Cloud Cover (%)	Pasquill Stability[a]	Aggregate Loaded Dumps	Aggregate Loaded Tons
15	0831	1018	61.2	51	S/12.6	5	D	86	150
16	1107	1226	59.1	57	S/14.0	20	D	80	150

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[a] Pasquill Stability Classes:
A - Extremely unstable
B - Unstable
C - Slightly unstable
D - Neutral
E - Slightly stable
F - Stable to extremely stable

Table 30. MEASURED DUST EMISSIONS (Crushed Stone Storage Piles)

Run	Background Concentration ($\mu g/m^3$)	Integrated Exposure (lb/ton)	Hi-Vol MMD[a] (μm)
15	334	0.11	1.4
16	334	0.11	-

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[a] Mass mean diameter of suspended dust, measured with Andersen high-volume cascade impactor.

Table 31. PLUME SAMPLING DATA (Aggregate Storage)

Run	Sampler Location: Height above Truck (ft)	Sampler Location: Lateral Displacement from Center of Truck (ft)	Sampling Rate (cfm)	Concentration (mg/m^3)	Unit Exposure (mg/in.^{2}/ton)
15	0	0	0.570	43.4	2.59
	3	4.5 Right	0.570	46.3	2.76
	3	1.5 Right	0.570	49.0	2.92
	3	1.5 Left	0.570	62.9	3.74
	3	4.5 Left	0.570	43.7	2.60
	6	0	0.570	27.5	1.64
	1.75[a]	1 Right	18	26.7	--
16	0	0	0.577	18.4	1.07
	3	4.5 Right	0.577	25.4	1.48
	3	1.5 Right	0.577	45.6	2.66
	3	1.5 Left	0.577	56.8	3.32
	3	4.5 Left	0.577	39.1	2.28
	6	0	0.577	63.2	3.68
	1.75[b]	1 Right	33.5	25.7	--

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a/ Andersen impactor.

b/ Standard high-volume sampler.

Also given in Table 30 is the mass mean diameter of suspended dust particles measured with the Andersen high-volume cascade impactor. The diameter values are aerodynamic measures which treat particles as equivalent spheres with a density of 2.5 g/cm^3. The complete size distributions is shown in Figure 19.

Two potentially significant sources of error in the particle size measurements as mentioned in Chapter 4 are:

1. The impactor samples nonisokinetically through the high-volume enclosure openings and collects large particles with low efficiency.
2. Unlike urban aerosol, aggregate particles are dry and brittle and are subject to bouncing and reentrainment from impaction surfaces.

Both of these factors cause apparent size determinations to be biased. in the direction of small diameter.

Table 32 gives the results of the laboratory analyses of the samples of aggregate from the test piles. Moisture content was determined by weight loss on over drying and particle size analysis by dry sieving.

As expected the moisture content of the aggregate was very low. This confirms near maximum dust generating potential of the aggregate.

The particle size analyses of the aggregate samples indicate that the 3/8-blend had more fine sand than the 1/2-straight rock, but slightly less silt. The size distributions are plotted in Figure 20.

The effective cut-off diameter for capture of dust by a standard high-volume sampler (or a high-volume cascade impaction operated within a high-volume enclosure) is taken to be 30 µm for a particle density of 2.5 g/cm^3. This value is based on (1) Lundgren's result, (2) the settling characteristics of aggregate particles and (3) the observed ratios of total high-volume concentration to isokinetic profiler concentration.

Computed Emission Factors

In the determination of emission factors for aggregate loadout, dust which settled out before reaching the exposure profiler (within 6 ft of drift distance from the downwind edge of the truck bed) was not included in the emission factor; these particles are larger than 150 µm for winds exceeding 10 mph.

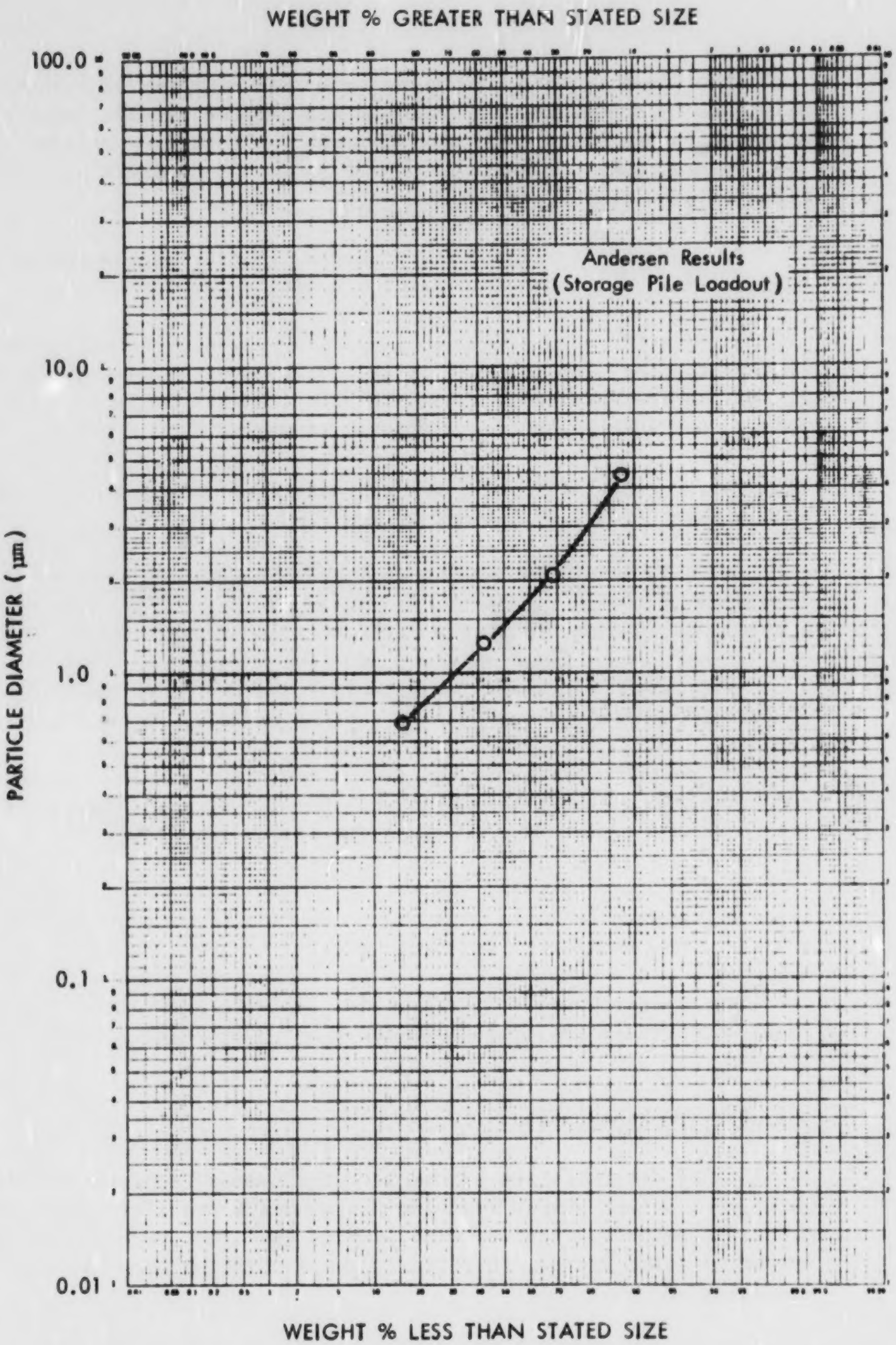

Figure 19. Particle size distribution--aggregate loadout emissions.

Table 32. AGGREGATE PROPERTIES (Crushed Stone Storage Piles)

Run	Aggregate (Type)	Age	Moisture (%)	Aggregate Size (% by weight)[a] Gravel (>2000 µm)	Coarse Sand (2000-420 µm)	Fine Sand (420-74 µm)	Silt (<74 µm)
15	3/8 in. Blend	1 week	0.3	97.3	0.3	1.1	1.3
16	1/2 in. Straight	1 week	1.1	94.9	2.5	0.7	1.9

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[a] Determined by dry sieving method.

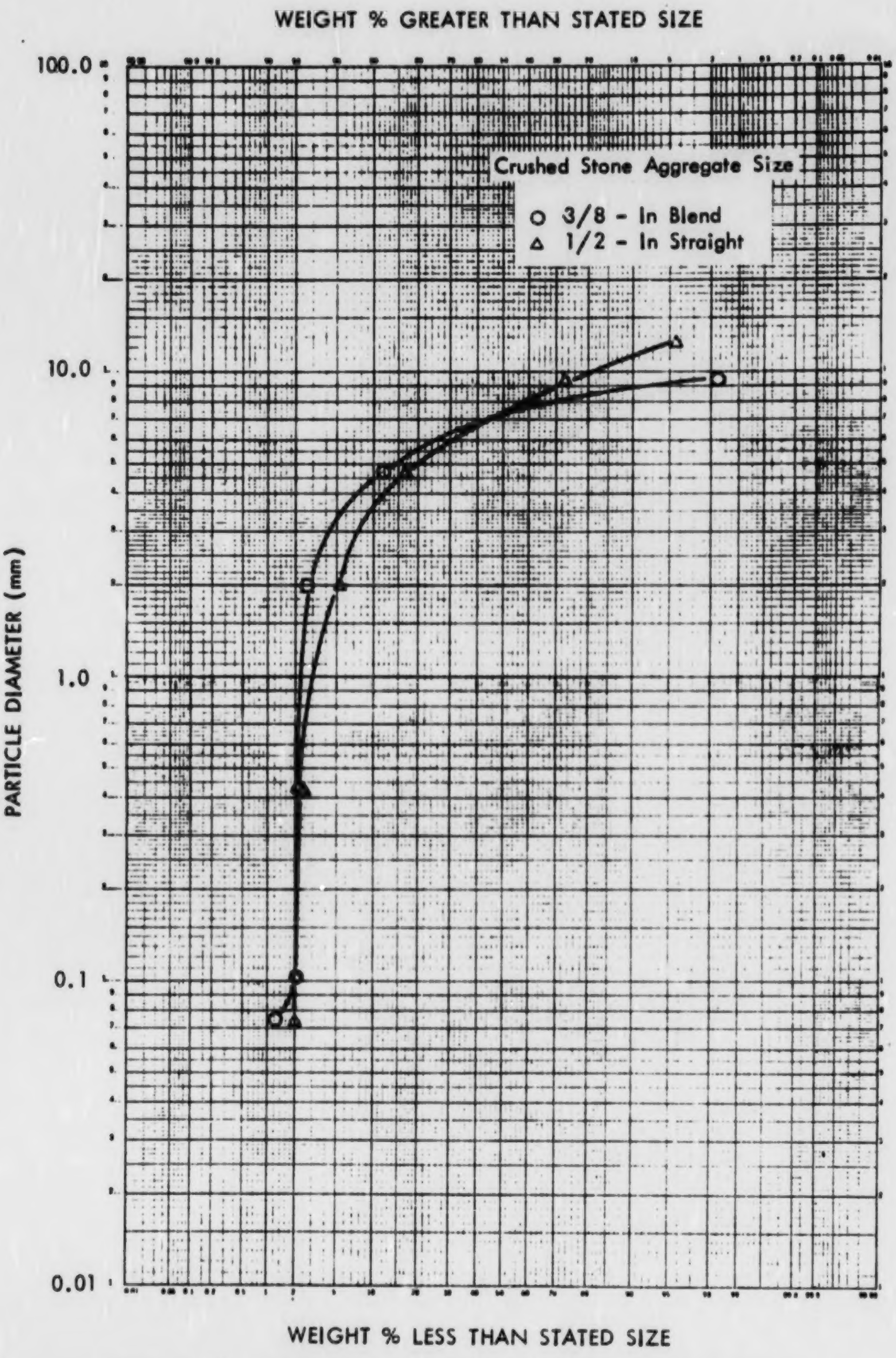


Figure 20. Aggregate size distribution--crushed stone.

The equations for calculation of the emission factors for three particle size ranges (< 2 μm, 2-30 μm, > 30 μm) are as follows:

$$e_{<2} = ER_6F_{<2}$$

$$e_{2-30} = ER_6(1 - F_{<2})$$

$$e_{>30} = E(1 - R_6) \quad ,$$

where e_i = mass of dust emissions with diameter i per ton placed in storage,
E = integrated exposure measurement,
R_6 = ratio of dust concentration measured by the standard high-volume sampler to the concentration measured by the isokinetic profiler, at 6-ft height,
$F_{<2}$ = fraction of the particles less than 2 μm in diameter, measured by high-volume cascade impaction.

The calculated emission factors are presented in Table 18.

Emissions during testing visually appeared to be very high, and may have approached a maximum for the following reasons:

1. The aggregate tested had been crushed within the previous week and had remained completely dry.
2. The wind velocity was high (beyond the point of incipient wind erosion).
3. The two sizes of aggregate were relatively small and contained a substantial amount of fines.

As indicated in Table 33 there is little difference in emission factors for the two sizes. Because the potential dust generation during these tests was near the maximum, an average value for the emission factor is thought to be about 0.05 lb/ton.

COMPARISON OF AGGREGATE EMISSION FACTORS

Total dust emissions from aggregate storage piles can be divided into the contributions of several distinct source activities which occur within the storage cycle:

1. Loading of aggregate onto storage piles,
2. Equipment traffic in storage area,
3. Wind erosion, and
4. Loadout of aggregate for shipment.

Table 33. CALCULATED EMISSION FACTORS
(Crushed Stone Storage Piles)

Run	Integrated Exposure (lb/ton)	Ratio Hi-Vol Catch: Profiler Catch	Fraction of Hi-Vol Catch < 2 μ	Emission Factors (lb/ton)[a]			Total
				d > 50 μm	2 < d < 50 μm	d < 2 μm	
15	0.11	0.48	0.67	0.057 (52%)	0.018 (16%)	0.035 (32%)	0.11
16	0.11	0.57	0.67[b]	0.047 (43%)	0.021 (19%)	0.042 (38%)	0.11

---

[a] d = partial diameter.
[b] Estimated value.

Although the test results presented in this chapter are limited, a comparison can be made to estimate the relative contributions of each of the source activities. The validity of the comparison of test results for different types of aggregate is best substantiated by the consistency of the data.

Table 34 shows the contribution of each source activity to the total dust emissions from aggregate storage piles. The total emission factor and the wind erosion contribution were determined from the testing in the Cincinnati area, and the contributions from the aggregate transfer operations were estimated from the results of the aggregate loadout tests in the Kansas City area. The contribution of vehicle traffic was determined by difference; its relatively high value is confirmed by visual observation of dust emissions from aggregate storage areas.

CORRECTED EMISSION FACTOR

Also shown in Table 34 are the correction parameters which differentiate the emissions potential of one aggregate storage area from another. For every contributing source activity, the correction parameter is climatic in nature. Overall the preceipitation-evaporation index best characterizes the regional variability of total emissions from aggregate storage piles. The PE index is 103 for Cincinnati and 96 for Kansas City.

The corrected emission factor which can be used to estimate the total amount of dust emissions with drift potential greater than 1,000 ft, i.e., particles smaller than 30 μm in diameter, is given by the following expression:

$$e(\text{aggregate}) = \frac{0.33}{(PE/100)^2} \quad ,$$

where e = emission factor (pounds per ton placed in storage), and
PE = Thornthwaite's precipitation-evaporation index.

Table 34. AGGREGATE STORAGE EMISSIONS BREAKDOWN

Source Activity	Correction Parameter	Emission Factor (total storage cycle) (lb/ton)	Approximate Percentage of Total
Loading onto piles	PE index	0.04	12
Vehicular traffic	Rainfall frequency	0.13	40
Wind erosion	Climatic factor	0.11	33
Loadout from piles	PE index	0.05	15
Total		0.33	100

CHAPTER 7

BUILDING CONSTRUCTION EMISSIONS

Under a separate contract from EPA, PEDCo-Environmental conducted a field investigation of atmospheric dust emissions from construction activities in the Southwest. A preliminary report[7] on the findings was submitted to EPA during February 1973. This section provides a further analysis of the sampling data from two construction sites in order to develop an emission factor for this source category and to evaluate several factors which affect the emission rate.

The original analysis of fugitive dust emissions from construction activities was based upon limited data available at the time of report preparation, and as such the conclusions derived therefrom were considered only preliminary. This supplemental evaluation is based upon all the sampling data which were collected at two locations, namely, Paradise Valley in Phoenix, Arizona, and a construction area in Las Vegas, Nevada. The conclusions which are derived from this larger data base, while not significantly different from the initial findings, do point to a slightly lower emission factor from construction activities.

The Paradise Valley construction site was an 80-acre residential development with a shopping center. Because atmospheric dust emissions from the construction activity were generated by diffuse and variable operations, conventional high-volume samplers, operated for 24-hr periods, were used to measure emissions.

PARADISE VALLEY CONSTRUCTION STUDY

Figure 21 shows the locations of six sampling stations in relation to the construction site in Paradise Valley. Samples were collected periodically at these stations between 31 August and 22 October 1972. A daily record of construction activity at the site was maintained throughout this period.

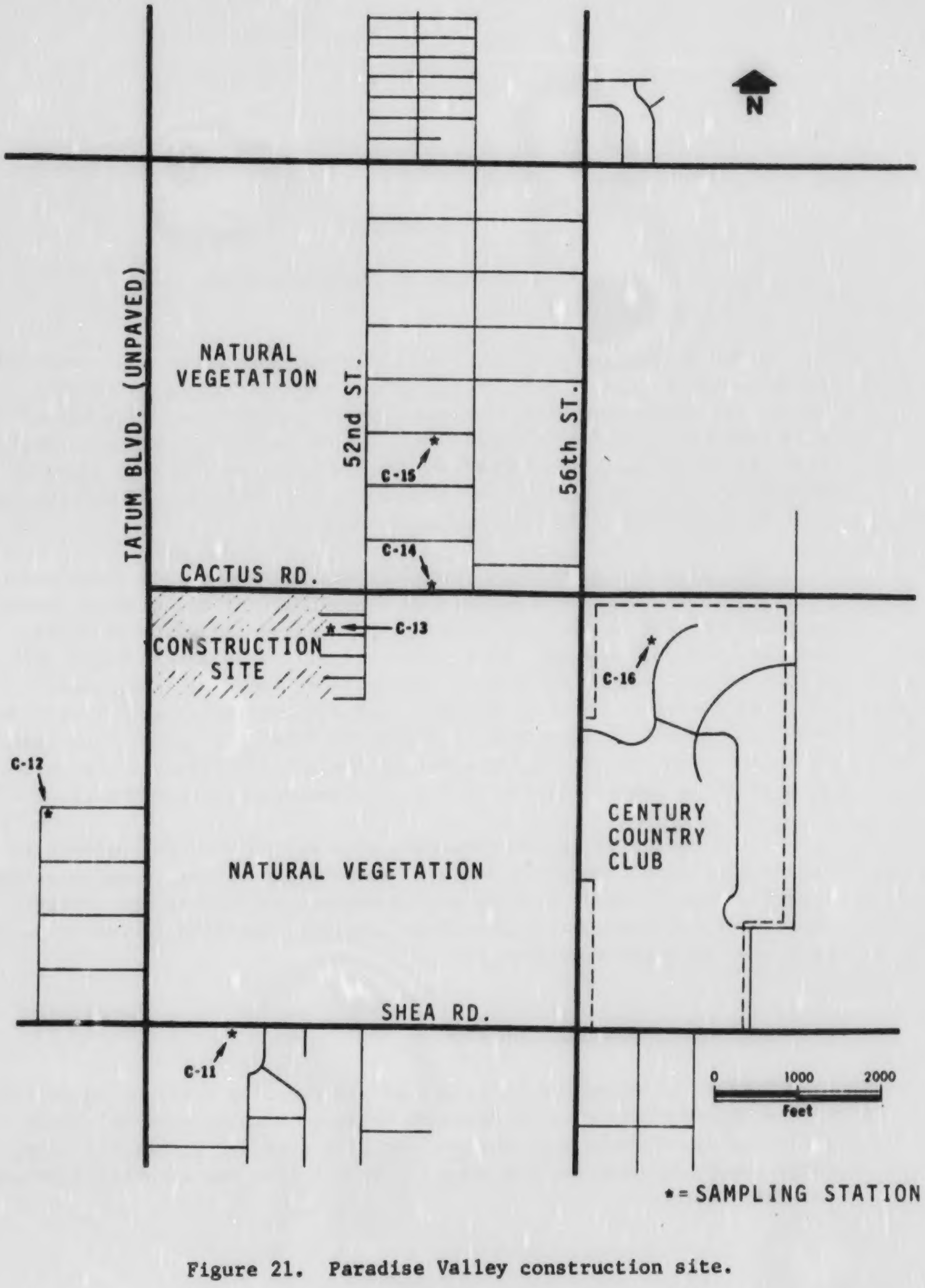

N
TATUM BLVD. (UNPAVED)
NATURAL VEGETATION
52nd ST.
56th ST.
C-15
C-14
CACTUS RD.
C-13
CONSTRUCTION SITE
C-16
C-12
CENTURY COUNTRY CLUB
NATURAL VEGETATION
SHEA RD.
C-11
0
1000
2000
Feet
* = SAMPLING STATION

Figure 21. Paradise Valley construction site.

Test Results

An examination of the particulate concentrations obtained at the sampling locations revealed that Station C-12 usually recorded abnormal values which were not representative of either normal background concentrations or concentrations expected to be contributed from the construction activity. An on-site examination earlier had revealed that this sampling location was far from an ideal exposure and therefore data obtained from this location were not used for evaluation purposes.

Station C-16 was located farthest from the construction site. Since it was seldom downwind from the site, it did not show an impact from construction activity. Consequently, data obtained from this location was also judged unsuitable for evaluation purposes.

Suspended dust concentrations measured at Stations C-11, C-13, C-14 and C-15, grouped according to wind directions, are listed in Table 35. This breakdown facilitated proper documentation of concentrations at background and downwind stations and subsequent evaluation of the contribution from the construction activity.

A cursory examination of pollution roses presented in Figure 22 indicates that the effect of the construction activity was reflected at sampling Stations C-13, C-14 and C-15 when they were downwind from the construction site. This occurred during periods when the wind was from the southwest quadrant, the predominant wind direction during the sampling period. Under these conditions, Station C-11 served as the background station. It had an average concentration of 130 $\mu g/m^3$.

Station C-13, located just east of the construction site, recorded an average concentration of about 260 $\mu g/m^3$. During the periods of southerly, southwesterly and westerly winds, this station recorded its highest concentrations. This definitely reflects the contribution from the construction site to the concentration at this location.

Station C-14, located northeast of the construction site, also reflects higher concentrations. The average concentration recorded at this site was about 225 $\mu g/m^3$. This was as expected in view of its relative distance from the construction site compared to C-13, but is definitely indicative of contribution from the construction activity.

It is also important to note that the respective ordinate lengths of the pollution rose for this station were smaller than those at Station C-13, a trend which has been exhibited at Station C-15 as well. Apparently there were no localized activities downwind from the construction site impacting on these sampling stations; the effect of the construction activity was

Table 35. SUSPENDED PARTICULATE CONCENTRATIONS ($\mu g/m^3$)
(Paradise Valley: 31 August - 22 October 1972)

	Wind Direction							
Station	**N**	**NE**	**E**	**SE**	**S**	**SW**	**W**	**NW**
C-11	219		137	105	203	347	152	28
			130	256	212	152	95	138
			160	155			163	102
				136			185	42
				129			170	114
								73
Average	219		142	156	208	250	153	83
C-13	254		236	130	353	461	212	168
			166	492	389	487	375	123
			285	349				47
				239				49
				201				127
Average	254		229	282	371	474	294	103
C-14	593		296	176	370	324	280	23
			161	296	258	368	251	166
			131	171			336	194
				187			312	49
				192			70	126
Average	593		190	204	346	346	250	112
C-15	105		117	163	328	363	169	65
			130	374	292	365	141	118
				198			240	24
				114			415	57
				94				78
Average	105		124	189	310	364	241	68

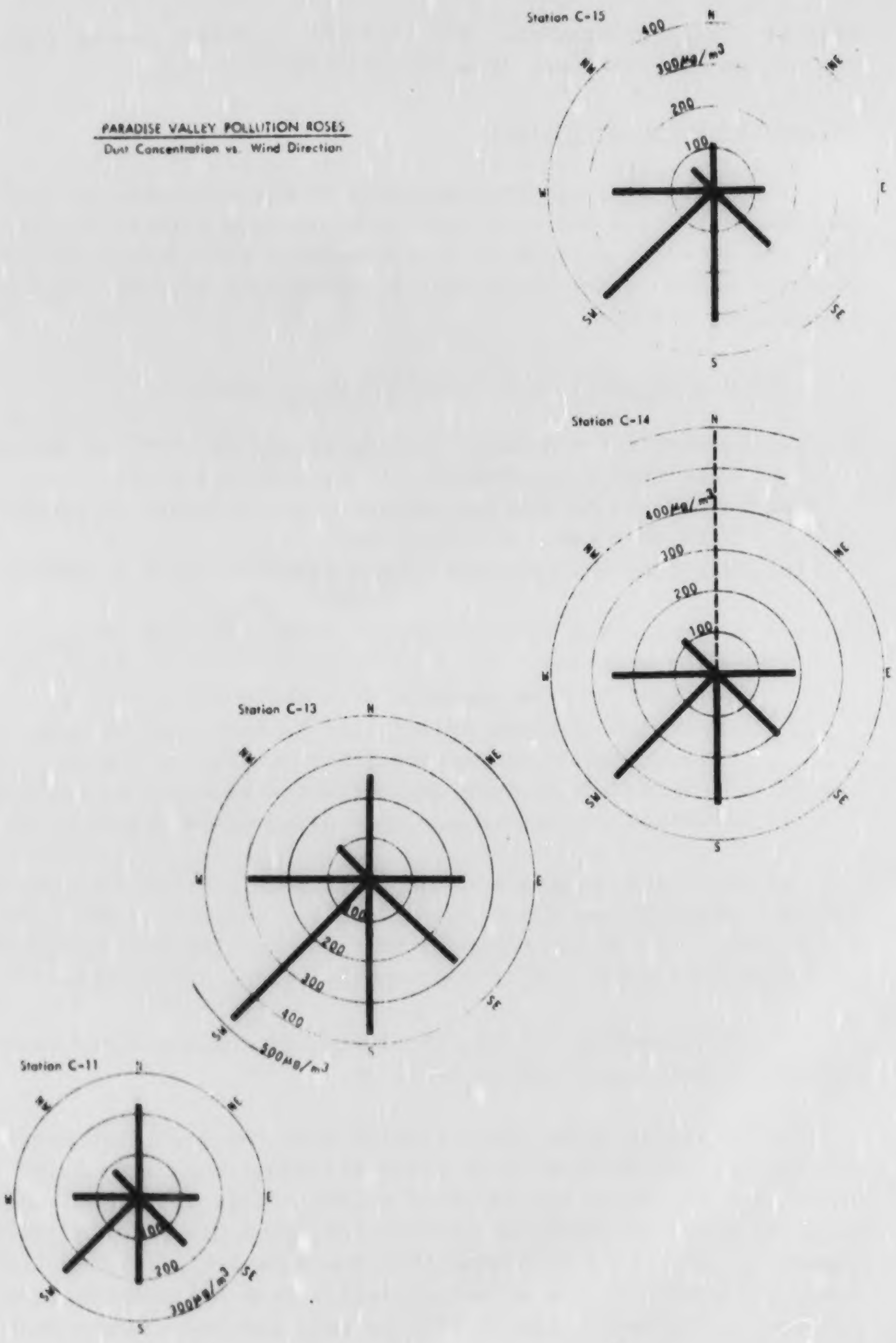


Figure 22. Pollution Roses - Paradise Valley Construction Site.

felt at all these stations, but to a progressively lesser degree depending on the distance away from the construction site.

Calculated Emission Factors

Since the wind was predominantly from the southwest quadrant during the sampling study and since the stations were aligned in that direction from the site, it was possible to determine the construction site source strength values using dispersion equation calculations. The procedure is outlined below.

For a particular wind direction of interest:

I. (a) Determine the average concentrations recorded at downwind stations (in this case, Stations C-13, C-14 and C-15).
   (b) Determine the average concentration recorded at background station (in this case, Station C-11).
   (c) Determine the source strength using dispersion equations.

II. (a) Determine the average concentration recorded at one of the downwind stations. For this purpose, it is desirable to use the closest station downwind from the construction site, since the distance of plume travel will be short and as such the cumulative effects of local terrain features will be small.
   (b) Determine the average concentration recorded at background station.
   (c) Determine the source strength using dispersion equations.

If the source strength values obtained in steps I(c) and II(c) above are approximately the same, and if similar values are obtained for S, SW, and W winds, it can be concluded that this estimation technique provides reproducible results and is descriptive of the actual emission rates.

The calculations for the three wind directions are presented in Appendix B and summarized in Table 36.

It is evident from these results that the source strength values calculated for the southwesterly winds are comparable and closer to each other than the other two pairs of values. This is probably because the sampling stations are lined up best for the southwesterly winds. Consequently, it may be concluded that the values of 1.37 and 1.41 tons/acre/month are closer to the actual emissions from the construction site. A value of 1.4 tons/acre/month will be used for the average dust emission factor.

Table 36. CALCULATED EMISSION FACTORS
(Paradise Valley Construction Site)

	Q, Emissions (tons/acre/month)	
Wind Direction	Based on C-13 Only	Based on Average of C-13, C-14 and C-15
Southwest	1.37	1.41
South	1.13	1.51
West	0.42	0.65

Correction for Activity Level

An activity log was maintained during the sampling period on daily activity level at the Paradise Valley construction site. Information obtained on the activity level was grouped into one of three categories--no activity, light to moderate activity, and heavy activity. Granted that such categorization was based more upon subjective evaluation rather than quantifiable parameters, it was hoped that such an analysis might yield a significant difference in respective fugitive dust emission rates.

Table 37 presents the measured particulate concentrations at the four sampling stations subdivided by activity level. The average concentrations for the various levels of activities do indicate a correlation between emission rate and activity level, as shown in Table 38.

Quantification of emissions associated with the level of activity should not be determined using just the above breakdown, since this breakdown includes data collection from all wind directions. Therefore, a further breakdown was made to separate the data collected when the wind was from the southwest quadrant (W, SW and S winds). This data analysis is shown in Table 39.

It is evident from Table 39 that there is not sufficient data to quantify the source emissions associated with each activity level. For the "no activity" category, there are insufficient data with, at best, one value. The comparison is further complicated by the fact that emissions were reduced during some of the sampling periods by application of water on the construction site.

For these reasons, it was not possible to quantify emissions associated with activity level. However, from the above two tables and from an examination of individual readings, it can generally be concluded that:

1. Light to moderate activity does not produce significantly higher emissions than no activity; and
2. Watering does not always show reduced emissions. This may be explained by the fact that watering is applied only on days that are extremely dusty or when heavy activity is expected.

LAS VEGAS CONSTRUCTION STUDY

Figure 23 shows the locations of five sampling stations in relation to the construction site in Las Vegas. The sampling program was conducted during the period between 21 August and 22 October 1972.

Table 37. ACTIVITY LEVEL VS PARTICULATE CONCENTRATION ($\mu g/m^3$)
(Paradise Valley)

	No Activity				Light/Moderate Activity				Heavy Activity			
Station	Date	Wind Dir.	Wind Speed	Concentration	Date	Wind Dir.	Wind Speed	Concentration	Date	Wind Dir.	Wind Speed	Concentration
C-11	9-30-72	W	5	185	9-20-72	W	2	95	8-31-72	SW	9	347
	9-2-72	SE	7	105	9-28-72	W	2	163	9-6-72	SW	3	152
	9-24-72	E	2	160	10-6-72	W	2	170	9-12-72	SW	6	152
	10-4-72	NW	2	28	10-2-72	SE	3	136	9-4-72	S	6	203*
	10-8-72	NW	2	138	9-18-72	E	2	137	9-14-72	S	7	212
	10-18-72	NW	3	42	9-22-72	E	2.5	130	9-8-72	SE	6	256
	10-22-72	NW	2	73	10-10-72	NW	2	102*	9-26-72	SE	1.5	155
	9-10-72	D.I.	8	97	10-20-72	NW	2	114*	10-16-72	SE	3	129
	10-14-72	D.I.	Calm	95					10-12-72	N	2	219
Avg.				103				131				203
C-13	9-2-72	SE	7	130	9-20-72	W	2	212	9-6-72	SW	3	461
	9-24-72	E	2	285	9-28-72	W	2	375	9-12-72	SW	6	487
	10-8-72	NW	2	168	10-2-72	SE	3	239	9-4-72	S	6	353*
	10-18-72	NW	3	47	9-18-72	E	2	236	9-14-72	S	7	389
	10-22-72	NW	2	127	9-22-72	E	2.5	166	9-8-72	SE	6	492
	9-10-72	D.I.	8	147	10-10-72	NW	2	125*	9-26-72	SE	1.5	349
	10-14-72	D.I.	Calm	186	10-20-72	NW	2	99*	10-16-72	SE	3	201
									10-12-72	N	2	254
Avg.				156				207				373
C-14	9-30-72	W	5	312	9-20-72	W	2	251	8-31-72	SW	9	324
	9-2-72	SE	7	176	9-28-72	W	2	336	9-6-72	SW	3	280
	9-24-72	E	2	113	10-6-72	W	2	70	9-12-72	SW	6	368
	10-4-72	NW	2	23	10-2-72	SE	3	187	9-4-72	S	6	370*
	10-8-72	NW	2	166	9-18-72	E	2	296	9-14-72	S	7	258
	10-18-72	NW	3	49	9-22-72	E	2.5	161	9-8-72	SE	6	296
	10-22-72	NW	2	126	10-10-72	NW	2	194*	9-26-72	SE	1.5	171
	9-10-72	D.I.	8	117					10-16-72	SE	3	192
	10-14-72	D.I.	Calm	205					10-12-72	N	2	593
Avg.				143				214				317
C-15	9-30-72	W	5	415	9-20-72	W	2	141	8-31-72	SW	9	363
	9-2-72	SE	7	163	9-28-72	W	2	240	9-6-72	SW	3	169
	10-8-72	NW	2	65	10-2-72	SE	3	114	9-12-72	SW	6	365
	10-18-72	NW	3	24	9-18-72	E	2	117	9-4-72	S	6	328*
	10-22-72	NW	2	76	9-22-72	E	2.5	130	9-14-72	S	7	292
	9-10-72	D.I.	8	103	10-10-72	NW	2	118*	9-8-72	SE	6	374
	10-14-72	D.I.	Calm	121	10-20-72	NW	2	57*	9-26-72	SE	1.5	198
									10-16-72	SE	3	94
									10-12-72	N	2	105
Average				138				131				254

* Indicates no watering applied
D.I. means direction indeterminate

Table 38. DUST CONCENTRATION VS ACTIVITY LEVEL

Station	Average Concentration ($\mu g/m^3$)		
	No Activity	Light to Moderate Activity	Heavy Activity
C-11	103	131	203
C-13	156	207	373
C-14	143	214	317
C-15	138	131	254
Average	135	171	287

Table 39. ACTIVITY LEVEL VS CONCENTRATION ($\mu g/m^3$) FOR W, SW AND S WINDS

Station	No Activity	Light to Moderate Activity	Heavy Activity
C-11	185	95	347
		163	152
		170	152
			203
			212
Average	185	143	213
C-13		212	461
		375	487
			353
			389
Average	--	294	423
C-14	312	251	324
		336	280
		70	368
			370
Average	312	219	336
C-15	415	141	363
		240	169
			365
			328
			292
Average	415	191	303

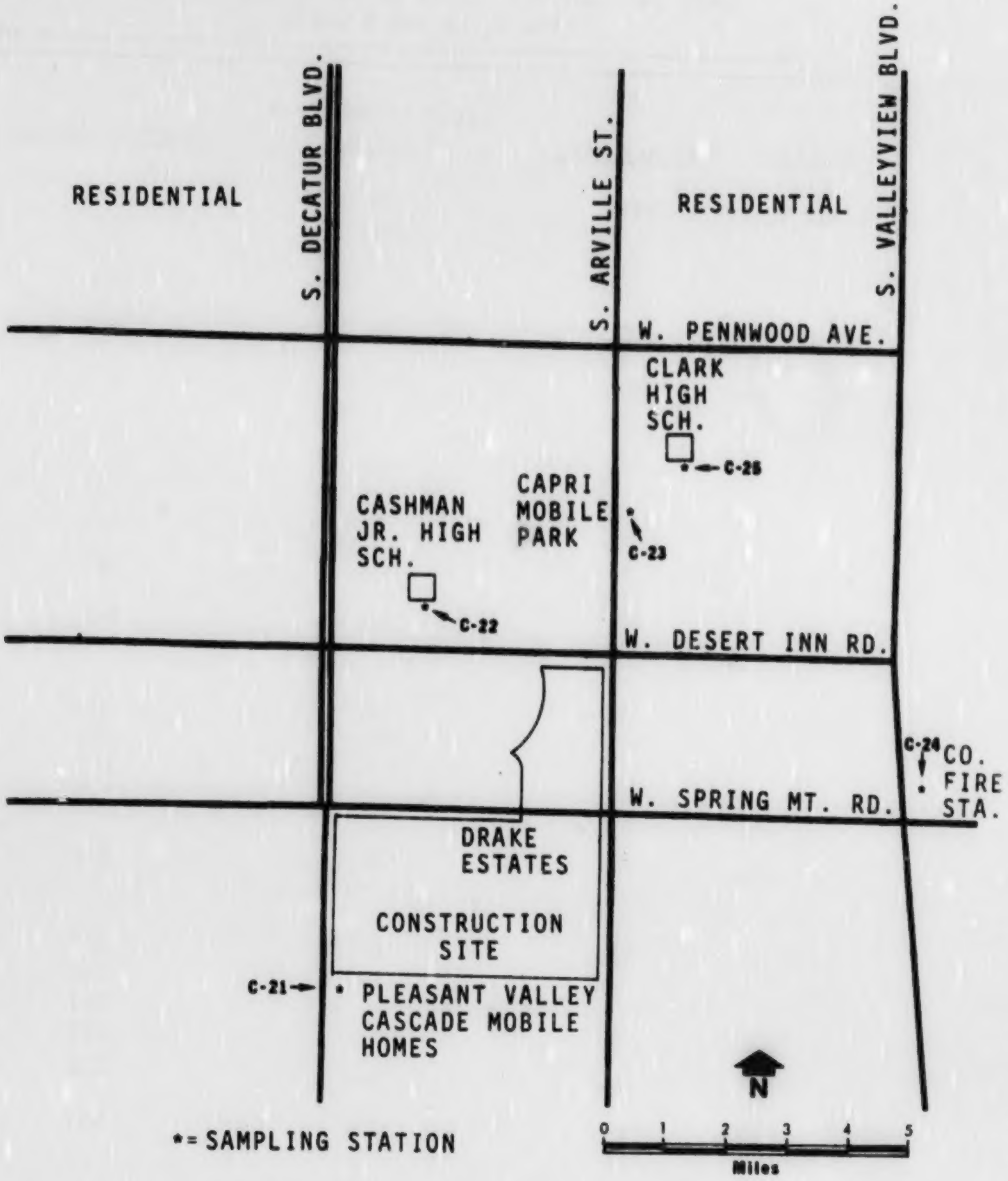

RESIDENTIAL
S. DECATUR BLVD.
S. ARVILLE ST.
RESIDENTIAL
S. VALLEYVIEW BLVD.
W. PENNWOOD AVE.
CLARK HIGH SCH.
C-25
CAPRI MOBILE PARK
C-23
CASHMAN JR. HIGH SCH.
C-22
W. DESERT INN RD.
C-24
CO. FIRE STA.
W. SPRING MT. RD.
DRAKE ESTATES
CONSTRUCTION SITE
C-21
PLEASANT VALLEY CASCADE MOBILE HOMES
N
*= SAMPLING STATION
0
1
2
3
4
5
Miles

Figure 23. Las Vegas construction site.

Test Results

Data collected during this sampling program have been grouped according to wind direction and are shown in Table 40, and in Figure 24 in the form of pollution roses for each sampling station.

An examination of tabulated data and the pollution roses developed therefrom indicates that Station C-21, which was located just south of the construction site (see Figure 23), recorded higher particulate concentrations during northerly winds than during the periods when the wind was from other directions. Therefore, it was concluded that the only local activity which contributed particulate emissions to this station was the construction activity under study.

Station C-22, which was located north of the construction site, recorded higher concentrations during southerly and southwesterly winds, which may be attributed to the construction activity. However, this sampling station also recorded high concentrations during northerly and westerly winds. With winds from those directions, the effect of the construction site should not be felt at this sampling station, thus strongly indicating that there were other localized activities in the vicinity of this station which contributed to higher concentration.

Data collected at Station C-23, which was located northeast of the construction site, also indicate possible contribution from localized activities other than the construction activity. This is evident from the higher concentrations recorded during northerly, northeast, southeast and perhaps westerly winds also. Higher concentrations recorded during southwesterly winds may be attributed to construction activity but can possibly be attributed to localized activities immediately west of the sampling station.

Station C-24 might have had interference from localized activities as evidenced by higher readings during northerly winds. The interfering source(s) could be the same located north of this station, which contributed to higher concentration at C-23 during southeasterly winds.

Station C-25, which was located on the premises of Clark High School, recorded concentrations comparable to expected ambient concentrations.

From the above analysis, it appears that all the sampling data collected at these stations cannot be used to evaluate the effect of the construction site activity because of possible interferences at some stations from other localized activities, even though the predominant wind as determined from the collected meteorological data was from the southwest and the locations of the sampling stations appear to be

Table 40. LAS VEGAS SITE - SAMPLE VALUES ($\mu g/m^3$)
SAMPLING PERIOD - 21 AUGUST - 22 OCTOBER 1972

Station	N	NE	E	SE	S	SW	W	NW
C-21	48	48		60	49	66	83	
	717	143		68		83		
	204	18		73		147		
	255			49		19		
						100		
						196		
						122		
						46		
						37		
						34		
						41		
						42		
						45		
Average	306	70		63	49	75	83	
C-22	46	56		64	122	38	102	
	314	97		69		125		
	152	44		52		127		
	71			80		126		
						151		
						79		
						220		
						135		
						80		
						99		
						132		
						94		
						104		
						263		
Average	146	66		66	122	127	102	
C-25		47		77		57	74	
				67		74		
				61		54		
						73		
						115		
						83		
						33		
						46		
						27		
						57		
						32		
						85		
Average		47		68		61	74	
C-23	102	109		89	85	228	127	
	336	205		196		300		
	112			142		238		
	133			164		236		
				188		128		
						194		
						104		
						127		
						148		
						69		
						139		
						71		
						37		
						68		
						76		
Average	171	157		156	85	144	127	
C-24	73	39		56	75	173	99	
	206	74		94		97		
	64	79		86		84		
	88			52		97		
				89		115		
						230		
						114		
						47		
						106		
						128		
						72		
						54		
						57		
						128		
Average	108	67		75	75	107	99	

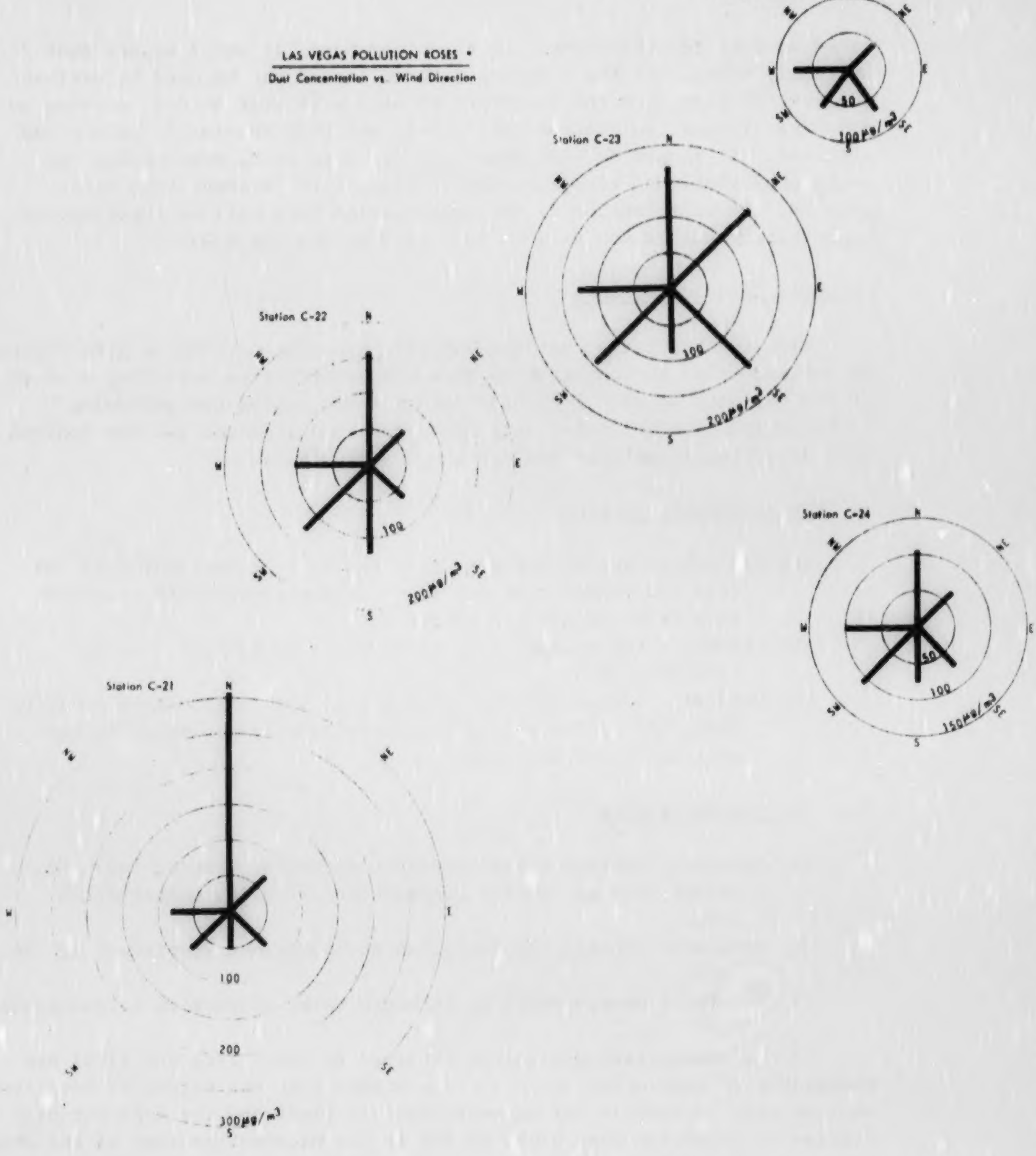


Figure 24. Pollution Roses - Las Vegas Construction Site.

lined up best for this wind. On the other hand, it would appear that for northerly winds, all the sampling data collected can be used to estimate the contribution from the construction site with Station C-21 serving as downwind station and Stations C-22, C-23 and C-25 serving as background stations. It should be mentioned that for this wind, even though the background stations' readings might reflect interferences from other sources, the contribution of the construction site will be superimposed upon these readings and will be reflected at Station C-21.

Computed Emission Factors

With the knowledge that the sampling stations originally were located to reflect only the contribution from the construction activity, a check on the validity of the collected data was made using the following methodology. The collected data have been separated out for the desired wind directional analysis and are given in Table 41.

I. For southwesterly wind

(a) Determine average concentration recorded at Stations C-22 and C-23 and assume this value to reflect particulate contribution from the construction site.
(b) Determine the average concentration at background station (Station C-21).
(c) Determine source emission strength of the construction activity using dispersion calculations (calculations similar to the ones performed earlier).

II. For northerly wind

(a) Determine average concentration recorded at Station C-21 and assume this to reflect contribution from the construction site.
(b) Determine average concentration at background Stations C-22 and C-23.
(c) Determine source emission strength using dispersion calculations.

If the source strength values obtained in steps I(c) and II(c) are comparable to each other, then we can assume that the effect of localized sources were negligible during southwesterly winds and the apparent distortion of pollution rose might be due to the micrometeorology of the study area. On the other hand, if these values are not comparable, then we can assume that the localized sources did have an effect in the recorded concentrations at some of these stations. In this case, the value determined in step II(c) for northerly wind can be considered to be representative of

Table 41. MEASURED CONCENTRATIONS DURING N, NE, S AND SW WINDS ($\mu g/m^3$)

Date	C-21	C-22	C-23	C-25	C-24	Wind Direc.	Speed
8-21-72	48	46	102	-	73	N	8
8-23-72	717	314	336	-	206		9
8-25-72	204	152	112	-	64		8
8-27-72	255	71	133	-	88		6
	Avg=306	Avg=146	Avg=71		Avg=108		Avg=7.8 mph
			Avg=142				
9-2-72	48	56	109	-	39	NE	7
9-4-72	143	97	-	-	74		9
9-18-72	18	46	205	47	79		8
	Avg=70	Avg=66	Avg=157		Avg=64		Avg=8.0 mph
			Avg=84				
10-8-72	49	122	85	46	75	S	11
8-29-72	66	38	228	-	173	SW	8
9-10-72	147	-	238	-	97		12
9-22-72	19	127	236	57	84		8
9-24-72	-	126	128	74	-		8
9-26-72	-	151	194	54	97		11
9-30-72	100	79	104	73	115		6
10-2-72	196	220	127	115	230		9
10-4-72	122	135	148	83	114		7
10-6-72	46	80	69	33	47		6
10-10-72	37	99	139	27	106		9
10-12-72	34	132	-	-	128		5
10-16-72	41	94	71	57	72		5
10-18-72	42	104	37	32	54		5
10-20-72	45	263	68	85	57		5
10-22-72	-	-	76	-	128		8
	Avg-75	Avg=127	Avg=130	Avg=63	Avg=107		Avg=7.5 mph
			Avg=107				

emissions from the construction site since there are no interferences surrounding Station C-21.

The results of the calculation exercise as outlined in steps I and II are given in Table 42.

It is apparent from Table 42 that the source emission strength values derived for southwesterly and northerly winds are not comparable to each other. Since the northerly wind direction apparently had the least interference from other emission sources, a "Q" value of approximately 1.0 tons/acre/month should be representative of the actual emission rate from this site.

Correction for Activity Level

An attempt was made to correlate the data obtained from the sampling program with the activity level at the construction site. The data were broken down into three categories of activity level (namely, no activity, light to moderate activity, and heavy activity) for each sampling station, as shown in Table 43. Within each category, further breakdown was made by grouping the data into different sectors of wind directions, and analyzing for any correlation which existed between the measured concentrations and the activity level. As can be seen from the summaries in Table 44, it is not possible to derive any meaningful correlation factors or to quantify the source emission strengths associated with each activity level.

The reasons for lack of any correlation are suspected to be the same as those for the Paradise Valley data: (a) the categorization of activity at the construction site into three groups was based upon subjective rather than definite emission quantifying parameters; and (b) apparent localized emissions surrounding some of the sampling locations in this study area possibly have rendered the data unsuitable for this type of analysis. It is of interest to note that the data collected during periods of northerly and northeasterly winds reflect a trend between expected concentration and activity level. However, these data are insufficient to quantify the emissions.

Table 42. RESULTS OF DISPERSION CALCULATIONS

Wind Direction	Receptor Station(s)	Background Station(s)	Stability Class	Q = Emission Strength g/sec	ton/year	ton/acre/month
Southwesterly	C-22, C-23	C-21	C	20.9	730	0.61
Southwesterly	C-22 only	C-21	C	20.3	703	0.59
Northerly	C-21	C-22, C-23	C	32.8	1,150	0.96

Table 43. LAS VEGAS CONSTRUCTION STUDY ACTIVITY LEVEL VS CONCENTRATION ($\mu g/m^3$)

	No Activity			Light/Moderate Activity			Heavy Activity		
Station	Date	Wind Dir.	Concentration	Date	Wind Dir.	Concentration	Date	Wind Dir.	Concentration
C-21	8-27-72	N	255	8-25-72	N	204	8-21-72	N	48
	9-2-72	NE	48	9-8-72	NE	60	8-23-72	N	717
	9-4-72	NE	143	9-18-72	NE	18	9-12-72	SE	68
	9-16-72	SE	49	9-22-72	SW	19	9-14-72	SE	73
	10-8-72	S	49	10-4-72	SW	122	8-29-72	SW	66
	9-10-72	SW	147	10-6-72	SW	46	8-31-72	SW	83
	9-30-72	SW	100	10-10-72	SW	37	10-2-72	SW	196*
				10-12-72	SW	34	10-20-72	SW	45
				10-16-72	SW	41			
				10-18-72	SW	42			
				9-28-72	W	83*			
Avg.			113			64			162
C-22	8-27-72	N	71	8-25-72	N	152	8-21-72	N	46
	9-2-72	NE	56	9-18-72	NE	46	8-23-72	N	314
	9-4-72	NE	97	9-22-72	SW	127	9-12-72	SE	64
	9-16-72	SE	52	9-26-72	SW	151	9-14-72	SE	69
	10-8-72	S	49	10-4-72	SW	135	9-20-72	SE	80
	9-24-72	SW	126	10-6-72	SW	80	8-29-72	SW	38
	9-30-72	SW	79	10-10-72	SW	99	8-31-72	SW	125
				10-12-72	SW	132	10-2-72	SW	225*
				10-16-72	SW	94	10-20-74	SW	263
				10-18-72	SW	104			
				9-28-72	W	102*			
Avg.			76			111			136
C-23	8-27-72	N	133	8-25-72	N	112	8-21-72	N	102
	9-2-72	NE	109	9-18-72	NE	205	8-23-72	N	336
	9-16-72	SE	164	9-8-72	SE	89	9-12-72	SE	196
	10-8-72	S	85	9-22-72	SW	236	9-14-72	SE	142
	9-10-72	SW	238	9-26-72	SW	194	9-20-72	SE	188
	9-24-72	SW	128	10-4-72	SW	148	8-29-72	SW	228
	9-30-72	SW	104	10-6-72	SW	69	8-31-72	SW	300
	10-22-72	SW	76	10-10-72	SW	139	10-2-72	SW	127
				10-16-72	SW	71	10-20-72	SW	68
				10-18-72	SW	37			
				9-28-72	W	127*			
Avg.			130			130			187
C-24	8-27-72	N	88	9-18-72	NE	79	8-21-72	N	73
	9-2-72	NE	39	9-8-72	SE	56	8-23-72	N	206
	9-4-72	NE	74	9-22-72	SW	84	8-25-72	N	64
	9-16-72	SE	52	9-26-72	SW	97	9-12-72	SE	94
	10-8-72	S	75	10-4-72	SW	114	9-14-72	SE	86
	9-10-72	SW	97	10-6-72	SW	47	9-20-72	SE	89
	9-30-72	SW	115	10-10-72	SW	106	8-29-72	SW	173
	10-22-72	SW	128	10-12-72	SW	128	10-2-72	SW	230
				10-16-72	SW	72	10-20-72	SW	57
				10-18-72	SW	54			
				9-28-72	W	99*			
Avg.			84			85			119
C-25	10-8-72	S	46	9-18-72	NE	47	9-12-72	SE	77
	9-24-72	SW	74	9-22-72	SW	51	9-14-72	SE	67
	9-30-72	SW	73	9-26-72	SW	54	9-20-72	SE	61
				10-4-72	SW	83	10-2-72	SW	115
				10-6-72	SW	33	10-20-72	SW	85
				10-10-72	SW	27			
				10-16-72	SW	57			
				10-18-72	SW	32			
				9-28-72	W	74*			
Avg.			64			51			81

* indicates no watering applied.

Table 44. LAS VEGAS CONSTRUCTION STUDY ACTIVITY LEVEL VS CONCENTRATION

Station	Wind Direction	Average Concentration (μg/m^3)		
		No Activity	Light to Moderate Activity	Heavy Activity
C-21	All Directions	113	64	162
C-22		76	111	135
C-23		130	130	187
C-24		84	85	119
C-25		64	51	81
C-21	S, SW	99	49	97
C-22		84	115	162
C-23		126	128	181
C-24		104	88	153
C-25		64	48	100
C-21	N, NE	149	94	383
C-22		75	99	180
C-23		121	159	219
C-24		67	79	114
C-25		--	47	--

SUMMARY AND CONCLUSIONS

The estimated emission values from the two construction sites in Phoenix and Las Vegas were 1.4 and 1.0 tons/acre/month, respectively. Based on the same methodology, except for the division of data into individual wind directions, the preliminary data (first half of sampling period) had indicated the values to be 1.8 and 1.0. The observed difference in estimated emission rates between the two construction sites is attributed to differences in soil texture and to meteorological factors such as frequency of precipitation, atmospheric turbulence, etc.

For development of an emission factor for widespread use, these two numbers should certainly not be considered as representative of the full range of emission rates that might be encountered. To the contrary, both sampling locations were in the desert southwest, and are therefore probably much higher than emission rates from similar construction projects located in more moderate climates. The average of the two values, 1.2 tons/acre/month, is recommended for use as the high end of the range for this factor, i.e., appropriate for application in arid areas with watering for dust control.

Construction activity levels were shown to influence emission rates from the sites significantly. However, this variation could not be quantified. The final factor represents emission rates during the period of active construction, including some days with no activity, some with moderate activity, and some with heavy earth-moving equipment and considerable truck traffic. Substantial error may result if the factor is applied to a site during a period of extended inactivity.

CHAPTER 8

EMISSIONS INVENTORY PROCEDURES

The rational development of an emissions control strategy for a county or other jurisdiction requires an adequate assessment of the nature and extent of air pollution in the region involved. This chapter outlines the procedures for inventorying the source categories treated in earlier chapters, by applying the corrected emission factor formulations.

SOURCE DATA REQUIREMENTS

Two types of data are needed for the emissions inventory:

- Measure of source extent and
- Parameters for correction factors.

The specific data requirements for each source category are presented in Table 45.

Based on information available to us at this time, the following data on source extent will have to be estimated:

1. Traffic volume on unpaved roads as a function of surface type,
2. Number of agricultural tilling operations as a function of crop grown, and
3. Acres per dollar value of construction, as a function of construction type.

With reference to the last item, MRI has developed factors for conversion of dollar value of construction to acres of construction for major construction categories. These factors are presented in Table 46.

Table 45. AREA SOURCE DATA

Source Category	Measure of Extent	Correction Parameter
Unpaved roads	Vehicle-miles traveled, by road type	. Average vehicle speed . Vehicle mix . Surface texture (silt content) . Surface moisture ("dry" days)
Heavy construction sites	Acres of active construction, by type of construction	. Soil texture (silt content) . Soil moisture . Activity index
Agricultural land tilling	Acres by crop grown	. Surface soil texture (silt content) . Surface soil moisture
Unpaved airstrips	Landing/take-off cycles	. Surface soil texture (silt content) . Surface soil moisture
Aggregate storage piles	Tons put through storage cycle	. Precipitation-evaporation index

Table 46. ACRES OF CONSTRUCTION - 1973

Type of Construction	Estimated Acres per $\$10^6$	1973 New Construction[29/] ($\$10^6$)	1973 Total Acres
Private residential	8.0	60,084	480,672
Private commercial	2.5	16,259	40,648
Private industrial	3.0	6,108	18,324
Highways and streets	25.0	10,350	258,750
		92,801	798,394
All other new construction		45,752	
Total new construction		138,553	

As indicated in Table 45, a frequently required climatic parameter for use in correcting emission estimates is Thornthwaite's precipitation-evaporation index. Figure 25 shows a map of PE values calculated from annual precipitation and temperature data. Figure 26 gives the conversion of PE values to the form used in the correction factor. The precipitation frequency for use in the corrected emission factor for unpaved roads, is shown in Figure 27.

PARTICLE DRIFT POTENTIAL

The impact of a fugitive dust source on the air quality depends on the drift potential of the particles injected into the atmosphere. This section presents a brief analysis of particle drift potential.

The distance that a dust particle will travel from its point of injection into the atmosphere depends on (1) the injection height of the particle, (2) the terminal settling velocity of the particle, and (3) the interaction of the particle with atmospheric turbulence. If the vertical velocity fluctuations of the turbulent air are of the same order as the terminal settling velocity of a particle, the drift potential of the particle is significantly increased.

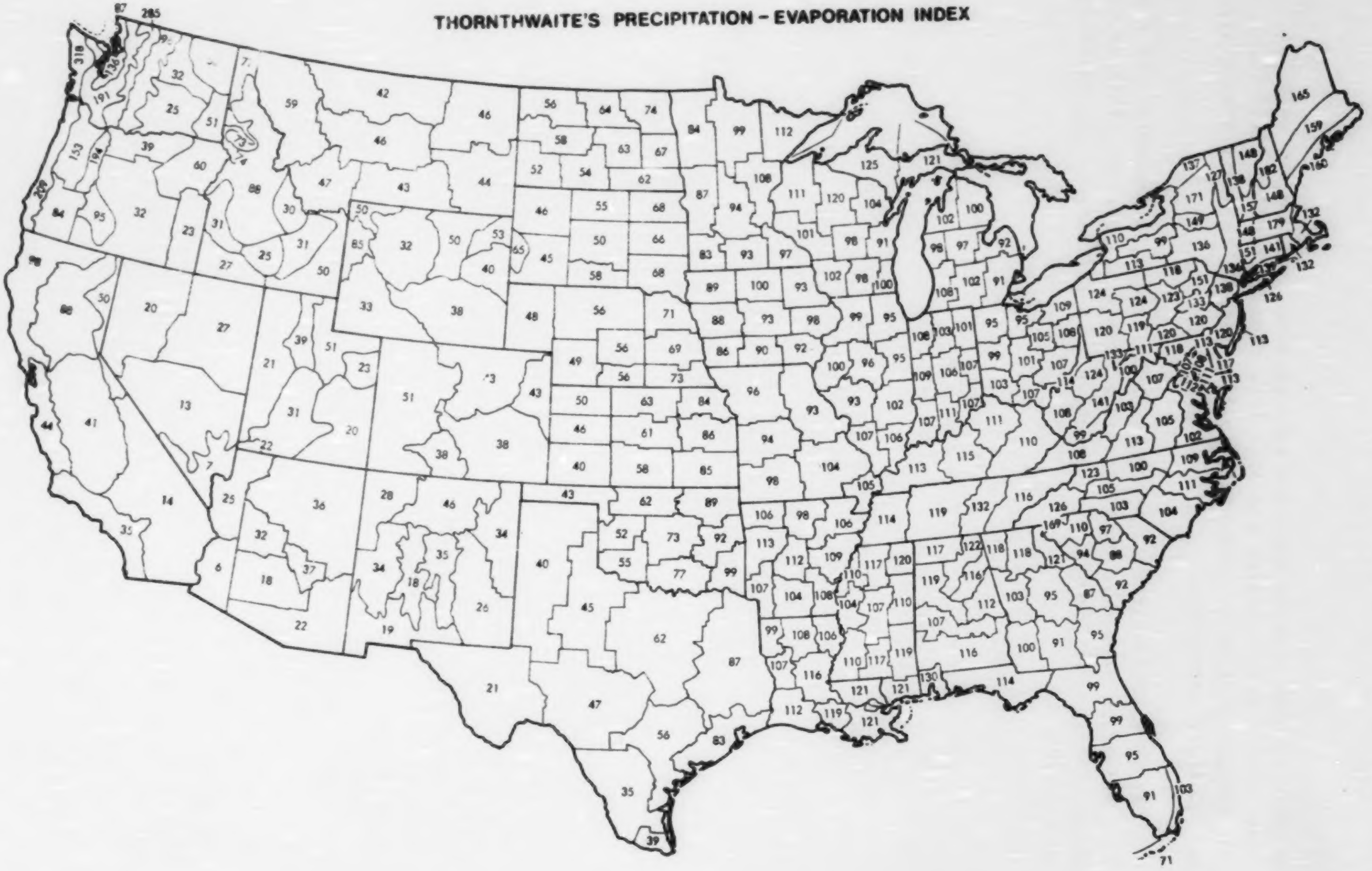
Using the fact that the root-mean square vertical velocity fluctuation is approximately proportional to the wind friction velocity,[30] Gillette and Blifford[16] have derived ratios of sedimentation velocity to friction velocity which represents the boundaries of extremes in particle behavior. These limits have been incorporated into Figure 28, which characterizes particle behavior as a function of aerodynamic particle diameter and wind speed. In the development of the curves shown, the friction velocity was calculated from reference wind speed (12-ft height) and an assumed roughness height of 1 cm (see Figure 2).

The area of Figure 28 labeled "suspension" describes those particles which have the potential for long-range transport in the atmosphere. For a given wind speed, this information can be used with the total emission factor and the particle size data to determine the long-range impact of dust emissions from a particular source.

WINDBLOWN DUST

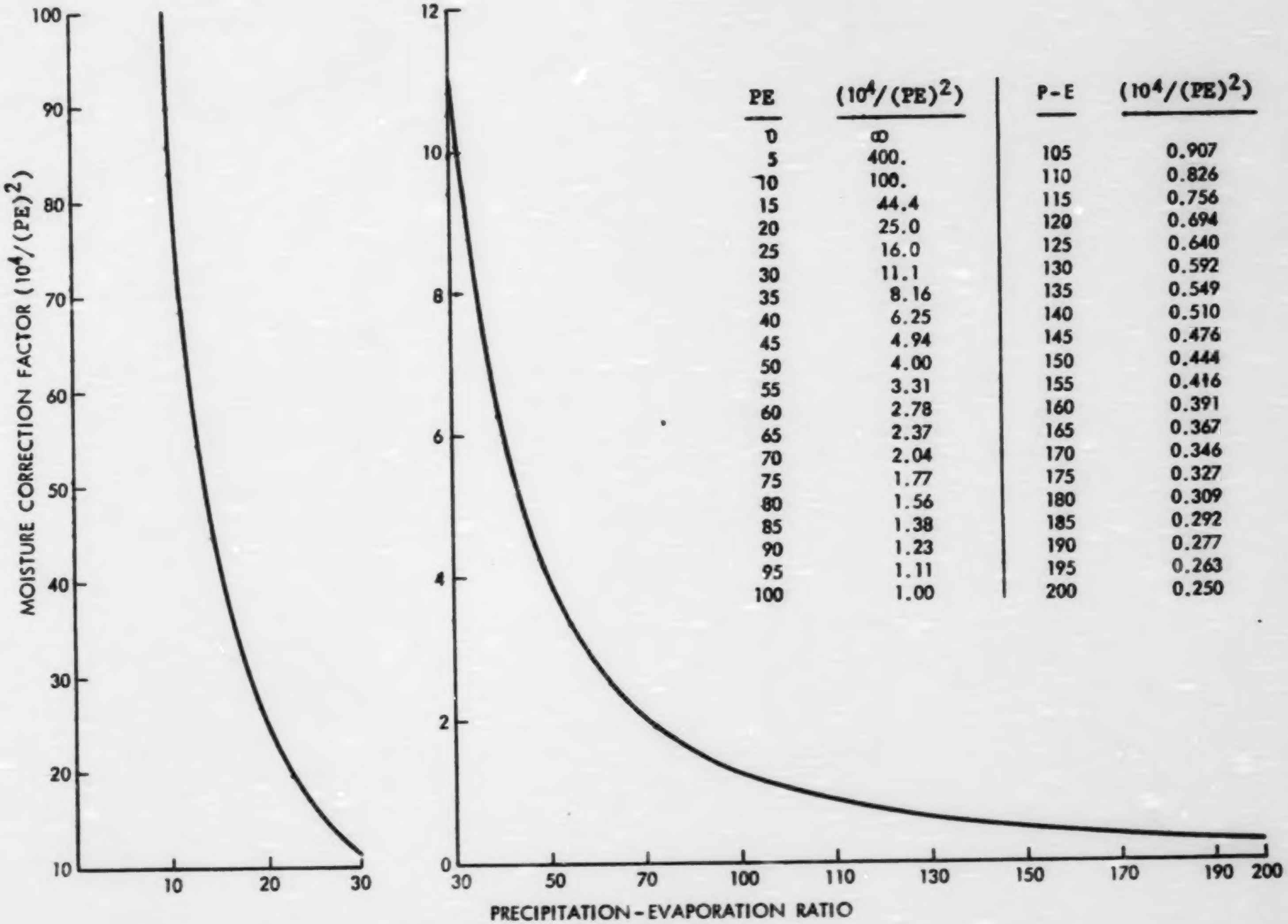
As discussed in Chapter 2, soil erosion by wind is recognized as an important source of atmospheric aerosol. However, relatively little is known about magnitude of the suspended dust fraction (a relatively minor portion) of wind erosion transport. Much of the information on the physics of wind erosion has been incorporated into the Wind Erosion Equation,[25] which relates the soil loss from an eroding field (i.e., the horizontal flux of sand-sized soil aggregate) to individual field and climatic parameters.

As part of the investigation reported herein, a procedure was developed for estimating suspended dust emissions from wind erosion. This procedure, which utilizes the Wind Erosion Equation as a starting point, is delineated in Appendix A.



THORNTHWAITE'S PRECIPITATION - EVAPORATION INDEX

Figure 25. Map of PE values for state climatic divisions.



PE	$(10^4/(PE)^2)$	P-E	$(10^4/(PE)^2)$
0	∞		
5	400.	105	0.907
10	100.	110	0.826
15	44.4	115	0.756
20	25.0	120	0.694
25	16.0	125	0.640
30	11.1	130	0.592
35	8.16	135	0.549
40	6.25	140	0.510
45	4.94	145	0.476
50	4.00	150	0.444
55	3.31	155	0.416
60	2.78	160	0.391
65	2.37	165	0.367
70	2.04	170	0.346
75	1.77	175	0.327
80	1.56	180	0.309
85	1.38	185	0.292
90	1.23	190	0.277
95	1.11	195	0.263
100	1.00	200	0.250

Figure 26. Moisture correction factors.

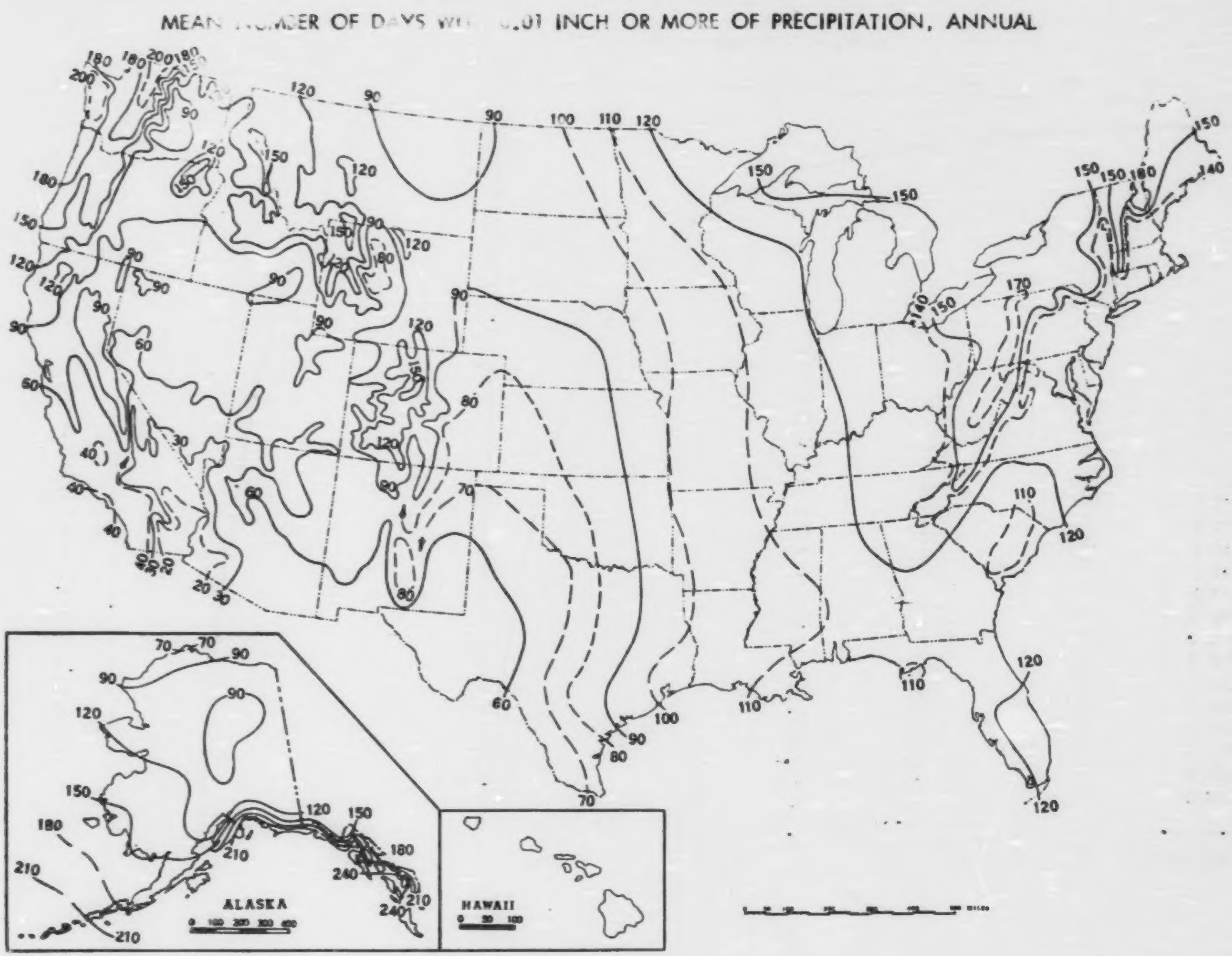

MEAN NUMBER OF DAYS WITH 0.01 INCH OR MORE OF PRECIPITATION, ANNUAL
ALASKA
0 100 200 300 400
HAWAII
0 50 100
180
200
150
120
110
100
90
80
70
60
40
30
20
170
140
210
240

Figure 27. Map of precipitation frequency.

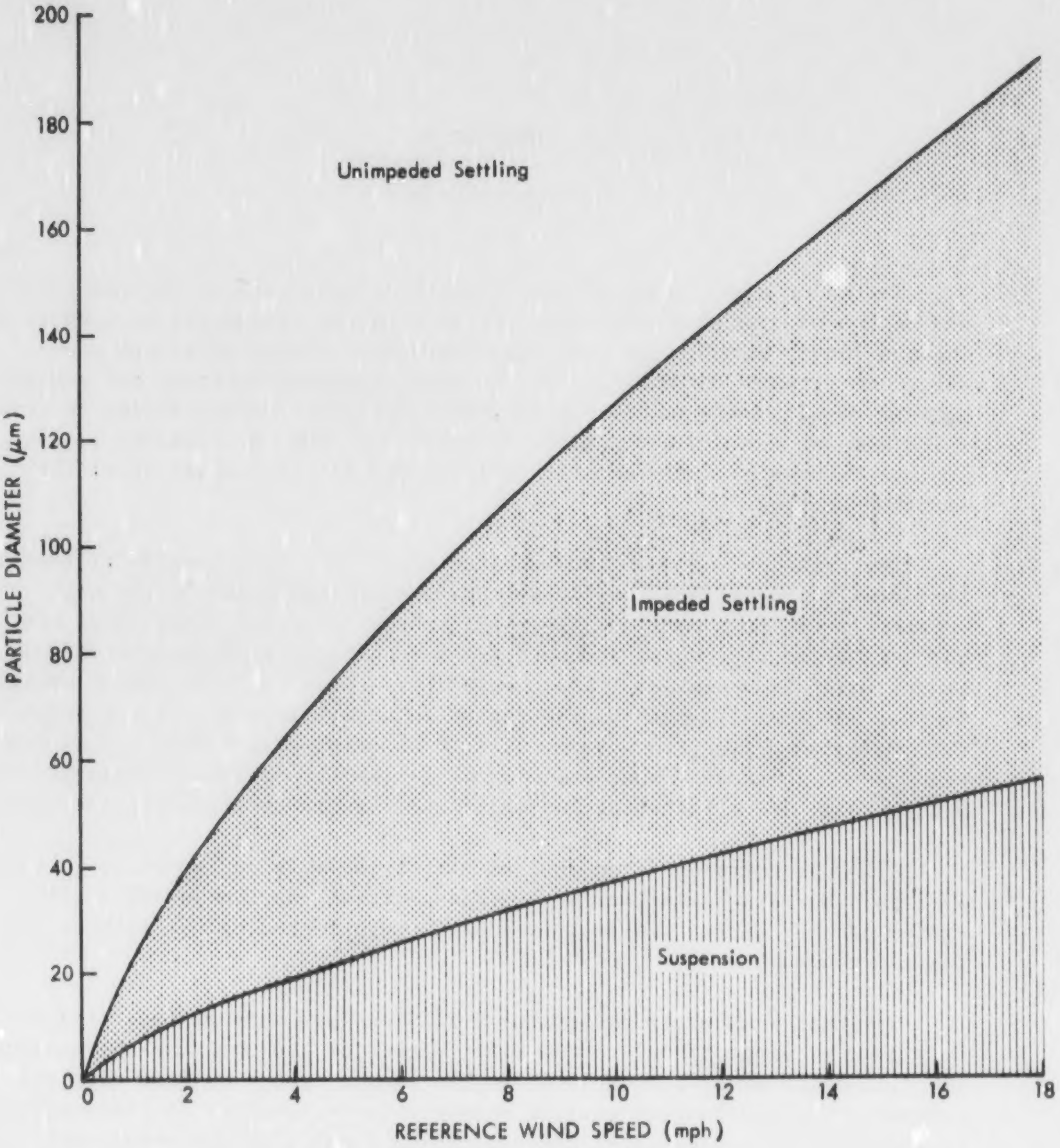


Figure 28. Particle settling/suspension regimes.

CHAPTER 9

CONCLUSIONS

The major conclusions of this investigation relate to the quantity and nature of dust emissions from the four source categories studied (i.e., unpaved roads, agricultural tilling, aggregate storage piles and construction sites). In addition to the basic emission factors, the analysis of test results has yielded significant information on correction factors which account for the variability of emissions from one locality to another because of differences in climate and in the properties of the emitting surface.

The emissions of dust from unpaved roads (per vehicle-mile of travel) is directly proportional to the average traffic speed and to the silt content of the road surface. The silt content of gravel roads does not vary significantly, which accounts for the uniformity of emissions from gravel roads with similar traffic patterns. Emissions are reduced during periods of rainfall, but quickly return to normal levels. Of the total dust emissions, i.e., those particles which drift beyond about 25 ft from the edge of the road, about one-fourth have localized impact, one-third have medium range drift potential and about half are in the fine particle range.

Although emissions from unpaved air strips were not measured in this program, the basic emission factor (mass emitted per landing/take-off cycle) and the correction factors can be approximated by the factors for unpaved roads.

The dust emitted by agricultural tilling (per acre of land tilled) is directly proportional to the silt content of the soil and the implement speed, and inversely proportional to the square of the surface moisture content. The equilibrium surface moisture for a locality is represented by Thornthwaite's precipitation-evaporation index. Of the total dust emissions, i.e., those particles which drift beyond 25 ft from the edge of the tillage path, about 40% have medium range drift potential and about one-third are in the fine particle range.

Dust emissions from aggregate storage piles (per ton of material put through the storage cycle) may be divided into contributions from four basic source activities:

1. Transfer to storage pile,
2. Equipment traffic in storage area,
3. Wind erosion, and
4. Loadout from storage pile.

Test results indicate that during a typical 3-month storage cycle, about 40% of the dust comes from road traffic in the storage area, 30% from wind erosion and 30% from aggregate transfer operations.

Emissions from medium-type construction activities could not be correlated with potential correction parameters because of the use of water for dust control and interferences from other dust sources. The values reported are thought to be fairly representative of uncontrolled emissions in less arid areas (PE ~ 50) than the Arizona-Nevada test sites, but having a similar soil silt content (~ 30%).

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APPENDIX A

PROCEDURE FOR ESTIMATING WINDBLOWN DUST

BACKGROUND

Only scattered information is presently available on total emissions of dust from agricultural areas. PEDCo-Environmental conducted field sampling studies with directional high-volume networks at two locations in the Southwest during 1972.[A1] The results indicated uniformly high concentrations at all sampling sites at both locations, but no emission factor could be established because both areas had such intensive farming that the contributions from individual fields could not be isolated.

The emission factor for tillage operations accounts for the limited periods when the farming equipment is actually used in the fields; it does not account for the lower level emissions that occur periodically as a result of wind erosion across the tilled fields. However, annual emissions from tilling may be quite small in comparison with suspended particulate emissions generated by wind erosion.

A recent report indicated that from 37 to 551 million tons of suspended particulate a year are created by dust storms in the 10 Great Plains states,[A2] with an average of 77 million tons per year during the 1960's. Based on these data, wind erosion contributes more particulate emissions than all other particulate source categories combined. The same publication estimated that 55 million acres of the approximately 70 million acres of land in the U.S. from which significant wind erosion occurs is active cropland. Even if these reported values are high by an order of magnitude, wind erosion emissions from agricultural lands are still far greater than those from the tillage operations, in areas where dust storms are common.

Estimation of the wind erosion emissions is not easily accomplished for several reasons:

1. The sources are not well defined in area and emissions are highly erratic over time; some sources are temporary and others are seasonal in nature;

2. Meteorological factors, themselves quite variable, cause large variations in emission rates due to factors such as periods between rainfall and frequency of high wind speeds and atmospheric turbulence;

3. Emission rate is a function of soil type, clod structure, and ridging of the fields;

4. Emission rates are not uniform for large areas;

5. Due to the high settling rate for agricultural dust, a large portion of the emissions fall out in the immediate area of their origin. Therefore, the point of measurement greatly affects the apparent emission rate; and

6. Wind erosion emissions from agricultural lands are indistinguishable in composition from naturally-occurring dust (background) from nearby non-agricultural areas.

APPLICATION OF WIND EROSION EQUATION

For the reasons outlined above, a major field sampling effort would be required to develop a comprehensive emission factor for suspended particulate emissions from wind erosion. As an alternative, it is proposed that a procedure developed by the U.S. Department of Agriculture for estimating topsoil losses from wind erosion be adapted for use in estimating emissions from tilled fields. This procedure, called the wind erosion equation, is thought to be appropriate because the same variables which affect the rate of topsoil losses also affect the generation of suspended particulate.

There are several arguments that can be presented for use of the wind erosion equation in this application and several reasons why it may not yield good results. These are summarized below:

Pro

1. Relationships in the basic wind erosion equation are based on extensive data and research;

2. The procedure considers several major parameters which affect the emission rate;

3. It requires input data which are usually readily obtainable; and

4. Its use of data descriptive of annualized and average conditions is acceptable since the procedure estimates long-term average emission rates (tons/year).

Con

1. The adaption assumes that a relatively constant percent of the total soil losses from tilled land becomes suspended, without any substantiating data;

2. Only sketchy data are available to provide any estimate of the percent of total soil losses that become suspended;

3. The procedure requires a complex series of calculations and much input data; and

4. It is not capable of estimating short-term emission rates.

It should be stated that the USDA researchers who developed the wind erosion equation are not in agreement with this application of the equation. Their objection is not clear, but it probably centers around the assumption that a constant fraction of the estimated soil losses become suspended. They cite data which indicates that from 3 to 40% of soil movement over test fields is in suspension rather than moving by surface creep or saltation. However, the material moved by "suspension" is not equivalent to the portion that is suspended particulate, because the former contains a significant amount of material that is settleable and falls out in proximity to its point of origin. Also, the range of suspended fraction is normally not as broad as indicated by the USDA data. These percentages are for extreme soil types which are probably not suitable for cropland.

The preliminary value proposed for percent suspended material is 2.5. This value was taken from the previous PEDCo study, where it was derived from particulate size distributions of soils and windblown material from agricultural lands. Obviously, the proposed number is subject to substantial modification based on better experimental data.

SIMPLIFIED VERSION OF WIND EROSION EQUATION

Presented below is a procedure for estimating windblown or fugitive dust emissions from agricultural fields. The overall approach and much of the data have been adapted from the wind erosion equation, which was developed as the result of nearly 30 years of research by the U.S. Department of Agriculture to predict topsoil losses from agricultural fields.

Several simplifications have also been incorporated during the adaptation process. The simplified format is not expected to affect accuracy in its present usage, since wind erosion estimates using the simplified equation are almost always within 5% of those obtained with the original USDA equation. Most of the input data are not accurate to ±5%.

WINDBLOWN DUST EQUATION

The modified equation is of the form:

$$E_s = AIKCL'V' \quad , \tag{1}$$

where: E_s = suspended particulate fraction of wind erosion losses of tilled fields, tons/acre/year
a = portion of total wind erosion losses that would be measured as suspended particulate, estimated to be 0.025
I = soil erodibility, tons/acre/year
K = surface roughness factor, dimensionless
C = climatic factor, dimensionless
L' = unsheltered field width factor, dimensionless
V' = vegetative cover factor, dimensionless.

As an aid in understanding the mechanics of this equation, "I" may be thought of as the basic erodibility of a flat, very large, bare field in a climate highly conducive to wind erosion (i.e., high wind speeds and temperature with little precipitation) and K, C, L' and V' as reduction factors for a ridged surface, a climate less conducive to wind erosion, smaller-sized fields, and vegetative cover, respectively.

This same equation can be used to estimate emissions from: (1) a single field, (2) a medium-sized area such as a valley or county, or (3) an entire AQCR or state. Naturally, more generalized input data must be used for the larger land areas, and the accuracy of the resulting estimates decreases accordingly.

PROCEDURES FOR COMPILING INPUT DATA

Procedures for quantifying the five variable factors in equation (1) are explained in detail below:

Soil Erodibility, I

Soil erodibility by wind is a function of the amount of erodible fines in the soil. The largest soil aggregate size normally considered to be erodible is approximately 0.84 mm equivalent diameter. Soil erodibility, I, is related to the percentage of dry aggregates greater than 0.84 mm as shown in Figure A-1. The percentage of non-erodible aggregates (and by difference the amount of fines) in a soil sample can be determined experimentally by a standard dry sieving procedure, using a No. 20 U.S. Bureau of Standards sieve with 0.84-mm square openings.

For larger areas than can be field sampled for soil aggregate size (e.g., a county) or in cases where soil particle size distributions are not available, a representative value of I for use in the windblown dust equation can be obtained from the predominant soil type(s) for farmland in the area. Measured erodibilities of various soil textural classes are presented in Table A-1.

If an area is too large to be accurately represented by a soil class or by the weighted average of several soil classes, the maps in Figures A-2A through A-2E and the legend in Figure A-2F can be used to identify major soil deposits and average soil erodibility on a regional basis.

Values of I obtained from Figure A-1, from Table A-1, or from the national soil maps can be substituted directly into equation (1).

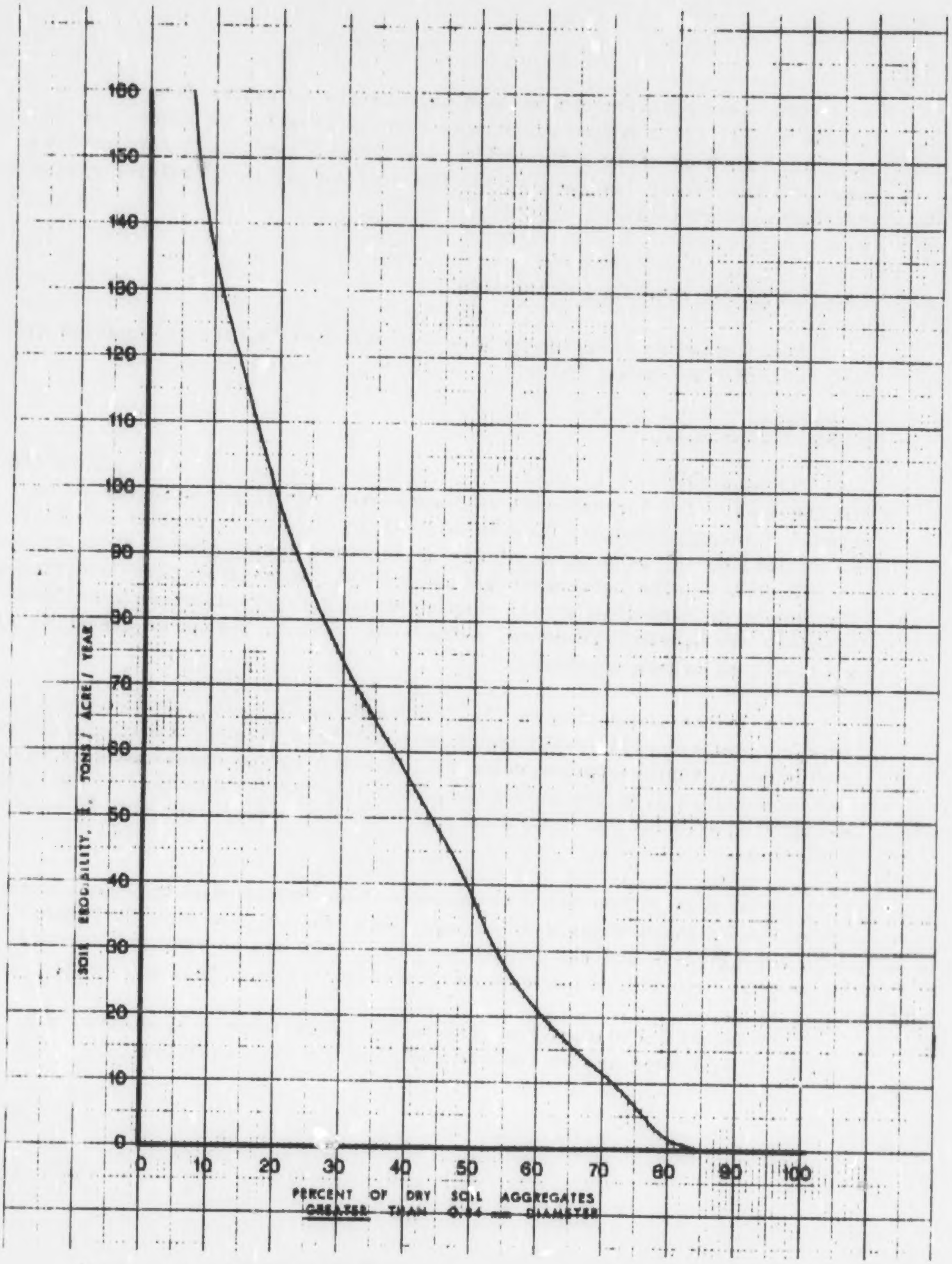


Figure A-1. Soil erodibility as a function of particle size.

Table A-1. SOIL ERODIBILITY FOR VARIOUS SOIL TEXTURAL CLASSES

Predominant Soil Textural Class	Erodibility, I, tons/acre/year
Sand*	220
Loamy sand*	134
Sandy loam*	86
Clay	86
Silty clay	86
Loam	56
Sandy clay loam*	56
Sandy clay*	56
Silt loam	47
Clay loam	47
Silty clay loam	38
Silt	38

*Very fine, fine, or medium sand

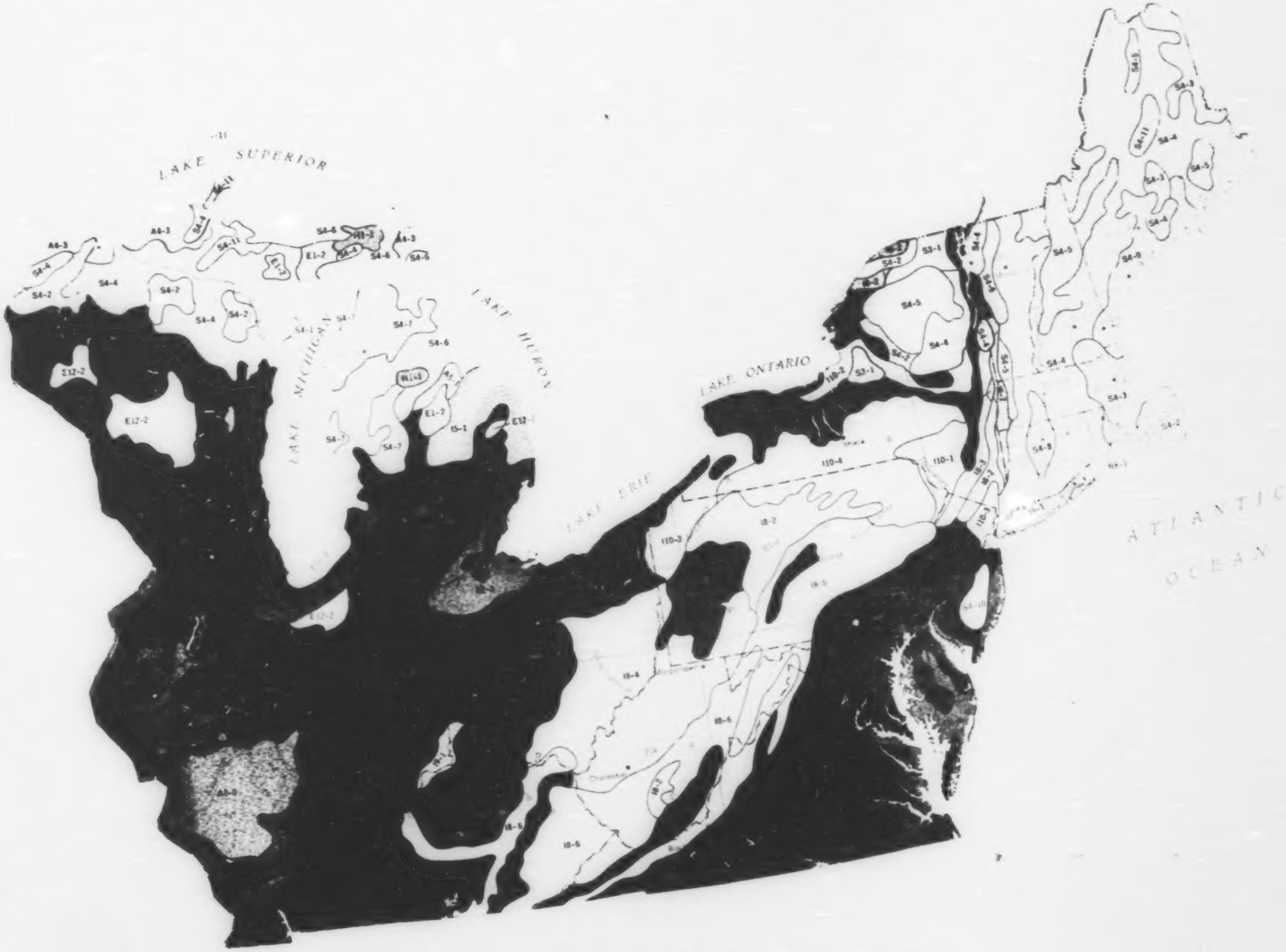

LAKE SUPERIOR
LAKE MICHIGAN
LAKE HURON
LAKE ERIE
LAKE ONTARIO
ATLANTIC OCEAN
A4-3
S4-4
S4-2
S4-11
E1-2
S4-6
S4-5
S4-7
E12-2
E12-1
E1-7
S3-1
110-2
110-1
110-3
110-4
I8-2
I8-5
I8-4
I8-6
S4-3
S4-9

Figure A-2A. Major soil types in northeastern states.

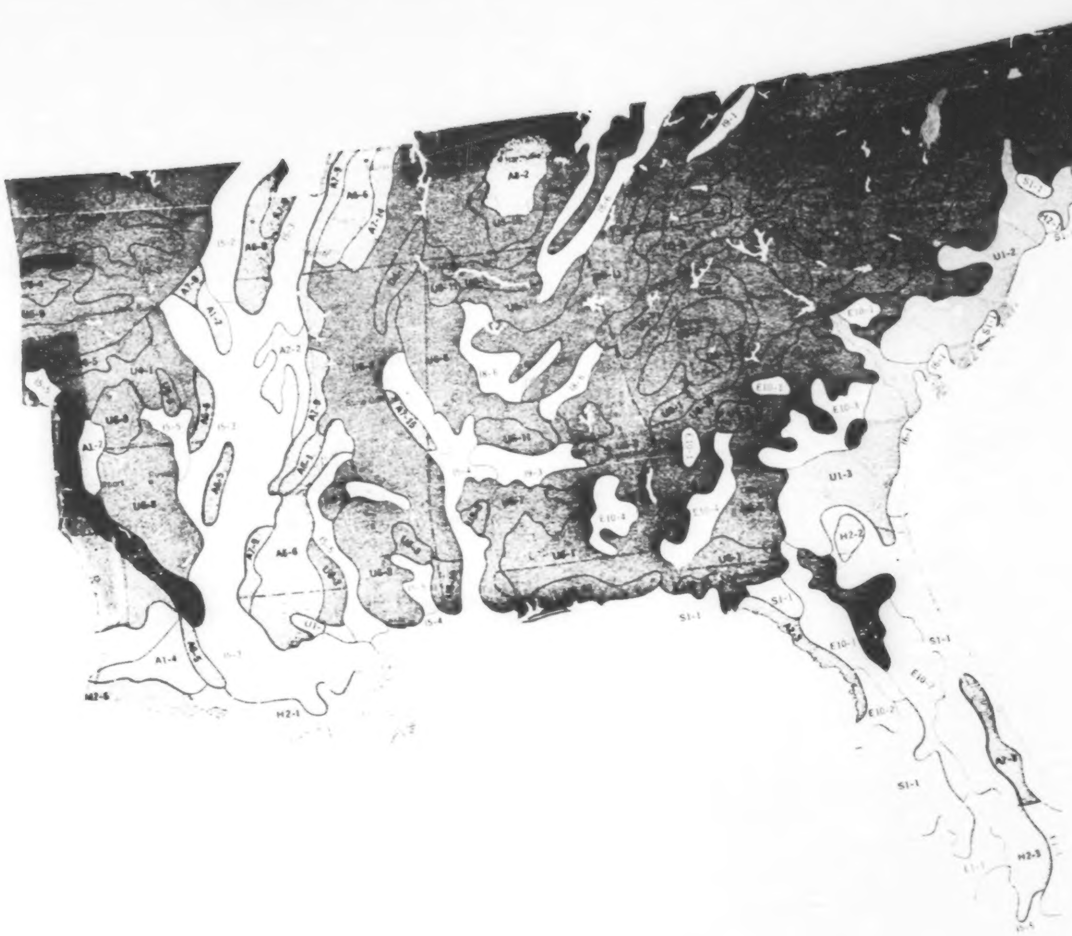

U1-2
U1-3
H2-2
A8-2
E10-4
E10-1
S1-1
H2-3
A7-2
A1-4
H2-1
M2-6
A1-2

Figure A-2B. Major soil types in southeastern states.

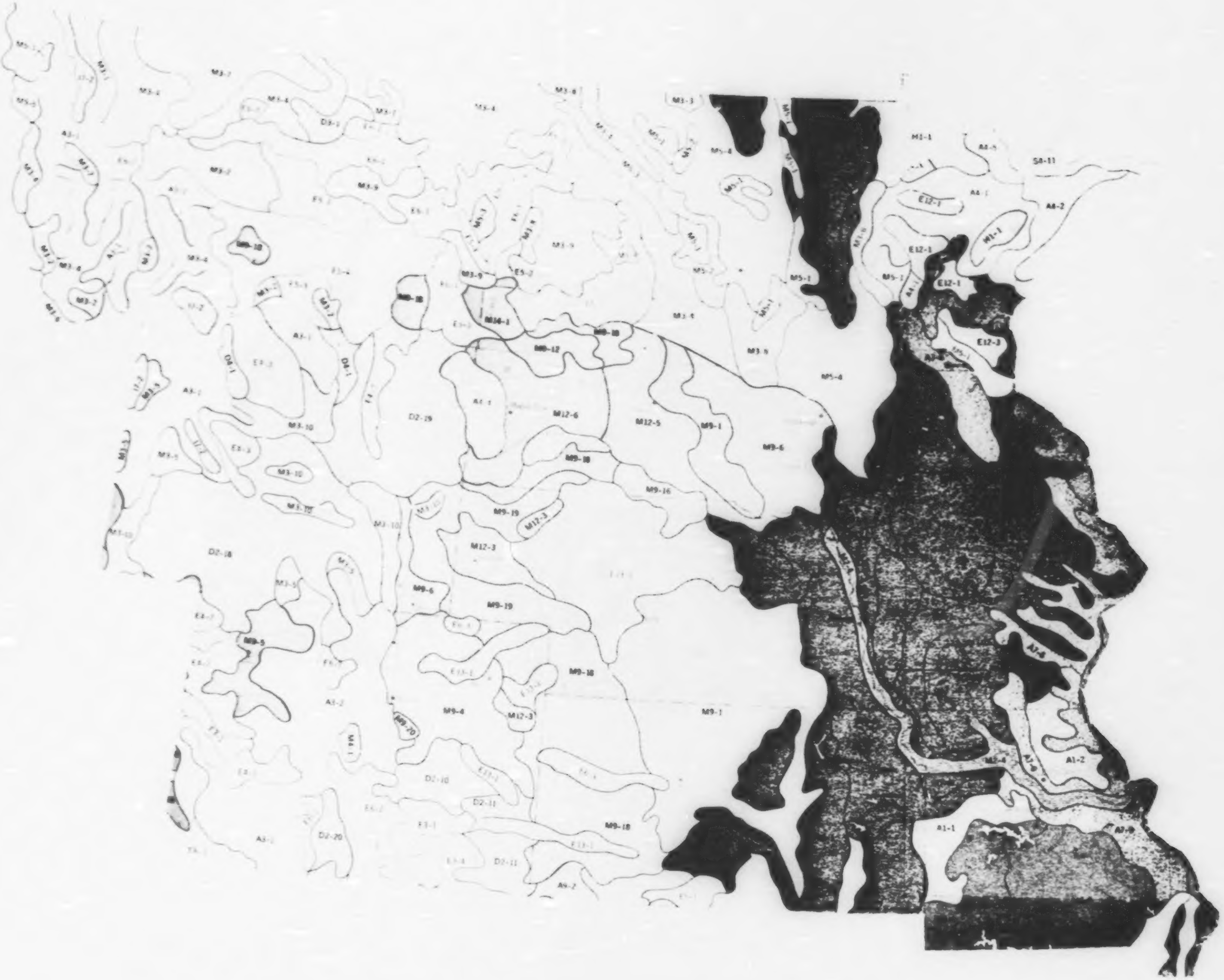
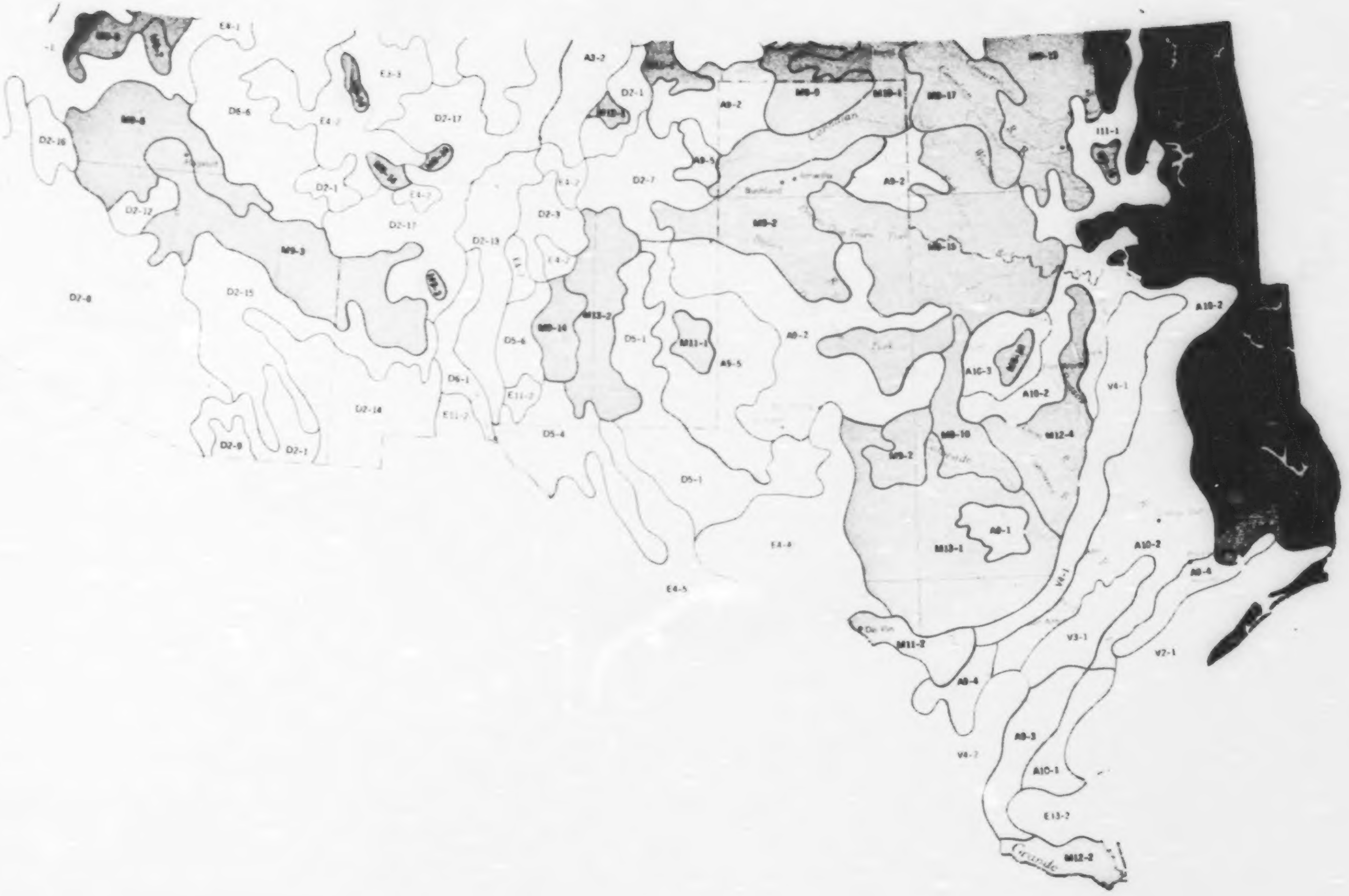

M3-7
M3-4
M3-8
M3-3
M3-2
M3-9
M5-4
M5-1
M1-1
A4-5
S8-11
A4-1
A4-2
E12-1
E12-3
M3-10
D2-29
D2-18
M12-6
M12-5
M9-1
M9-6
M9-18
M9-16
M9-19
M12-3
M9-12
M9-4
M9-20
M9-5
M4-1
D2-10
D2-11
D2-20
A1-2
A1-1
A7-9
A7-8

Figure A-2C. Major soil types in the northern Great Plains states.



E4-1
A3-2
E3-3
D6-6
D2-16
D2-17
E4-2
D2-1
D2-7
D2-12
D2-17
D2-3
D2-13
M9-3
D2-8
D2-15
D5-6
M13-2
D5-1
M11-1
A9-5
D6-1
E11-2
D2-14
D2-9
D2-1
D5-4
D5-1
E4-4
E4-5
M9-17
M9-15
M9-2
I11-1
A10-2
A10-3
A10-2
V4-1
M12-4
M9-10
M9-2
M13-1
M11-2
A8-4
V4-2
A8-3
A10-1
E13-2
M12-2
V3-1
V2-1
A10-2
Canadian
Grande

Figure A-2D. Major soil types in the southwestern states.

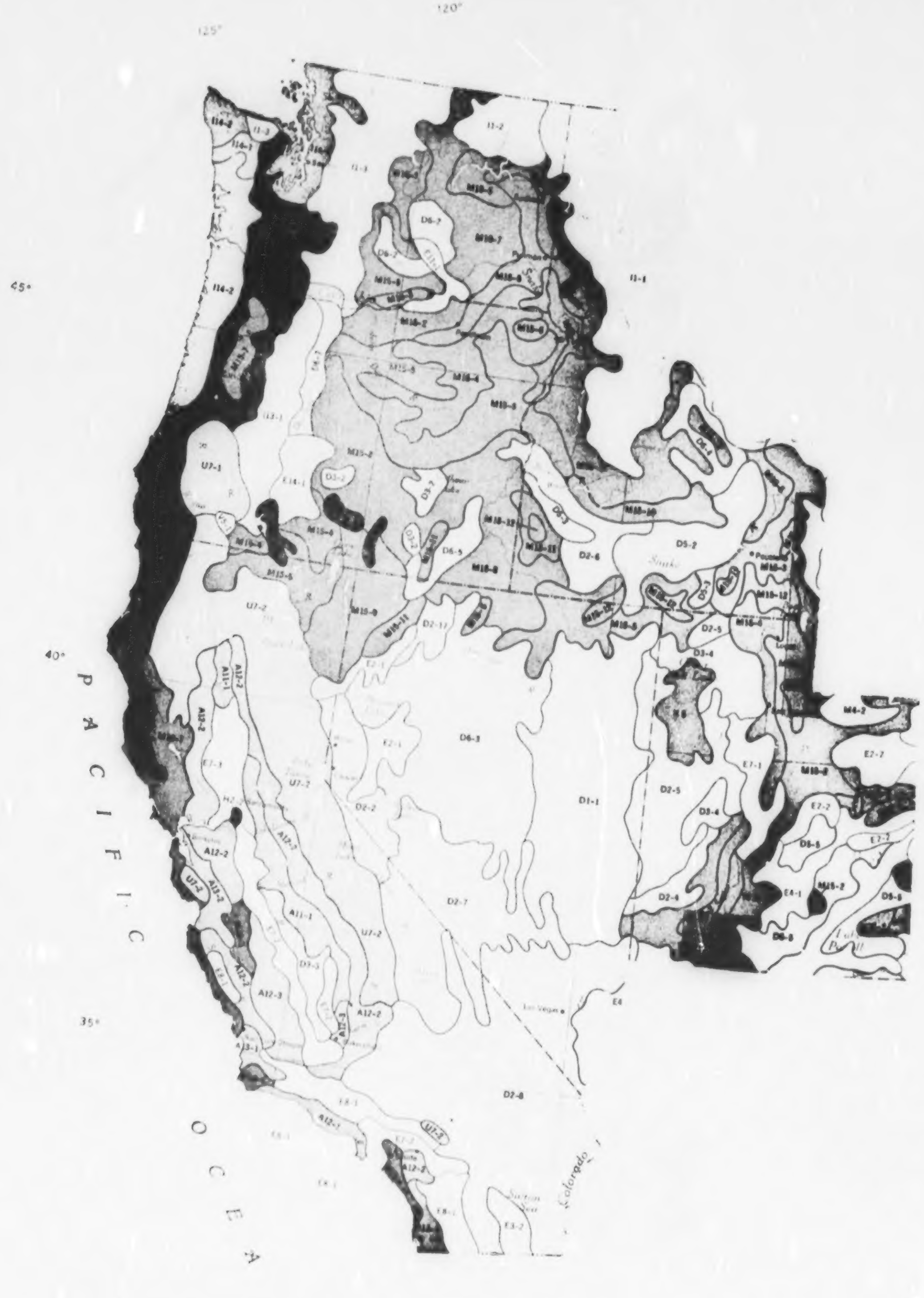

120°
125°
45°
40°
35°
P A C I F I C
O C E A
I14-2
I14-1
I1-2
I1-1
M10-7
D6-2
M15-2
U7-1
U7-2
E14-1
D3-2
D6-5
M10-8
M10-10
D2-6
D5-2
Snake
D2-5
D3-4
M4-2
E2-2
E7-1
E7-2
D6-3
D1-1
D2-7
D2-4
E4-1
A11-1
A12-2
A12-3
A13-1
D2-2
D2-8
Las Vegas
E4
Colorado
Salton Sea
E3-2

Figure A-2E. Major soil types in the western states.

SYMBOL	SOIL TYPE
A1, A2	Seasonally wet soils with subsurface clay accumulation
A3- A5	Cool or cold soils with subsurface clay accumulation
A6- A8	Clays
A9, A10	Burnt clay soils
A11- A13	Dry clay soils with some cementation
D1- D6	Arid soils with clay and alkali or carbonate accumulation
E1	Poorly-drained loamy sands
E2	Loamy or clayey alluvial deposits
E3- E8	Shallow clay loam deposits on bedrock
E9	Loamy sands in cold regions
E10, E12	Loamy sands in warm regions
E11, E13, E14	Loamy sands in warm, dry regions
H1, H2	Wet organic soils; peat and muck
I1	Ashy or amorphous soils in cold regions
I2	Infertile soils with large amounts of amorphous material
I3	Fertile soils of weathered volcanic ash
I4	Tundra; frozen soils
I5, I6	Thin loam surface horizon soils
I7	Clay loams in cool regions
I8- I10	Wide varying soil material with some clay horizons
I11	Rocky soils shallower than 20 inches, to bedrock
I12	Clay loams in warm, moist regions
I13	Clay loams in cold regions
I14	Clay loams in temperate climates
M1- M4	Surface loam horizon underlain by clay
M5	Shallow surface loams with no underlying clays
M6- M8	Surface loamy soils
M9- M14	Semiarid loams or clay loams
M15, M16	Dry loams
O1, O2	Clays and sandy clays
S1- S4	Sandy, clay, and sandy clay loams
U1	Wet silts with some subsurface clay accumulation
U2- U6	Silty loams with subsurface clay accumulation
U7	Dry silts with thin subsurface clay accumulation
V1- V2	Clays and clay loams
V3- V5	Silty clays
X1- X5	Barren areas, mostly rock with some included soils

Figure A-2F. Legend for soil maps in Figures A-2A through A-2E.

Surface Roughness Factor, K

This factor accounts for the resistance of wind erosion provided by ridges and furrows or large clods in the field. The surface roughness factor, K, is a function of the height and spacing of the ridges, and varies from 1.0 (no reduction) for a field with a smooth surface to a minimum of 0.5 for a field with the optimum ratio of ridge height (h) to ridge spacing (w).

The relationship between K and $\frac{h^2}{w}$ is shown in Figure A-3. The value of K to be used in equation (1) should be rounded to the nearest 0.1 because of the large variations inherent in ridge measurement data. In cases where there are extreme variations of h or w within a field, determination of the K value should be limited to either 0.5 for a ridge surface or 1.0 for an unridged surface.

For county or regional areas, K can best be determined as a function of crop type, since field preparation techniques are relatively uniform for a specific crop. Average K values of common field crops are shown in Table A-2. When the K (or L' or V') factors are based on crop type, separate calculations of windblown dust emissions must be made for each major crop in the survey area. This procedure is explained and demonstrated later in this presentation.

Climatic Factor, C

Research has indicated that the rate of soil movement by wind varies directly as the cube of wind velocity and inversely as the square of soil surface moisture. Surface moisture is difficult to measure directly, but precipitation-evaporation indices can be used to approximate the amount of moisture in soil surface particles. Therefore, readily available climatic data can provide a quantitative indicator of relative wind erosion potential at any geographic location.

The C factor has been calibrated using the climatic conditions at the site of much of the research--Garden City, Kansas--as the standard base (C = 1.00). At any other geographic location, the C factor for use in equation (1) can be calculated as:

$$C = 0.345 \frac{W^3}{(PE)^2} , \qquad (2)$$

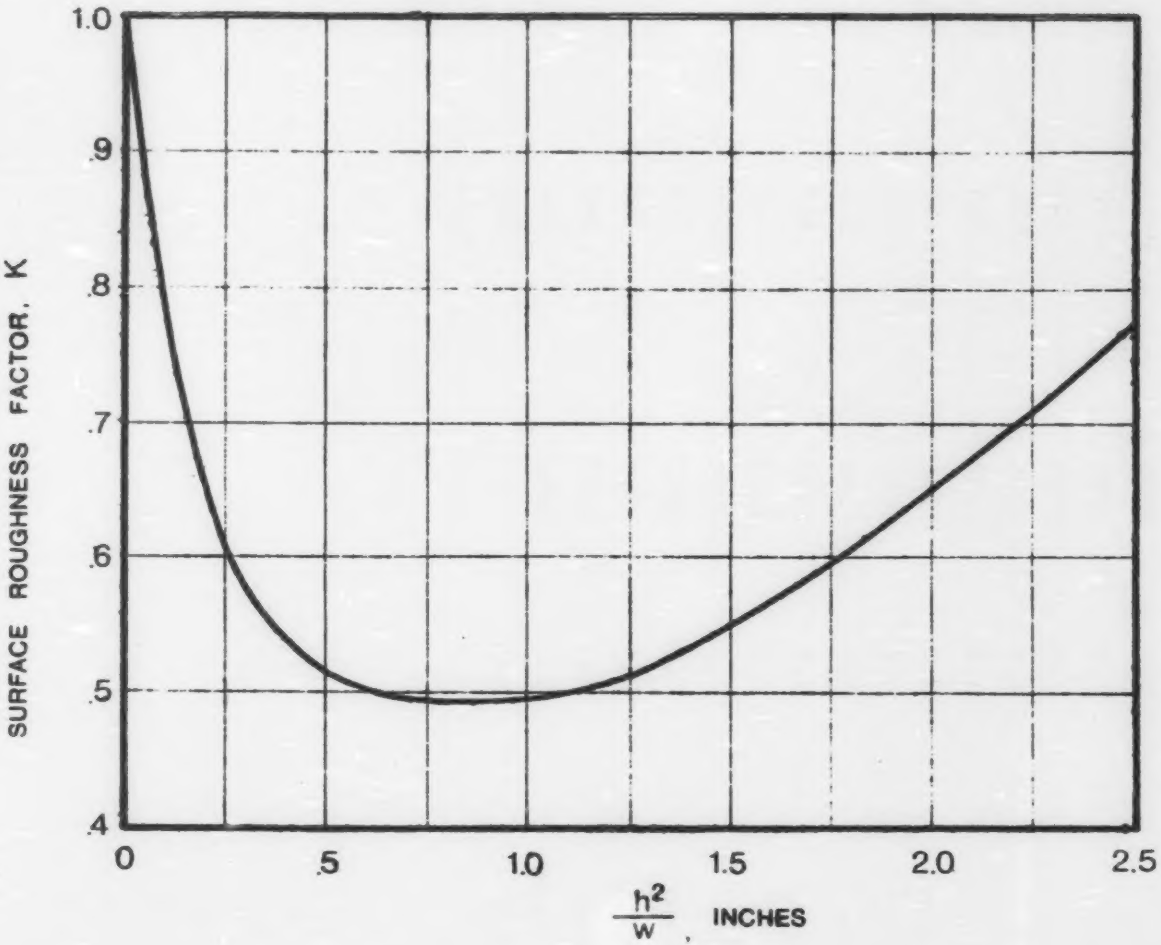


Figure A-3. Determination of surface roughness factor.

Table A-2. VALUES OF K, L AND V FOR COMMON FIELD CROPS

Crop	K	L,ft.	V,lb/acre
Alfalfa	1.0	1000	3000
Barley	0.6	2000	1100
Beans	0.5	1000	250
Corn	0.6	2000	500
Cotton	0.5	2000	250
Grain Hays	0.8	2000	1250
Oats	0.8	2000	1250
Peanuts	0.6	1000	250
Potatoes	0.8	1000	400
Rice	0.8	1000	1000
Rye	0.6	2000	1250
Safflower	1.0	2000	1500
Sorghum	0.5	2000	900
Soybeans	0.6	2000	250
Sugar Beets	0.6	1000	100
Vegetables	0.6	500	100
Wheat	0.6	2000	1350

where: W = mean annual wind velocity, in mph, corrected to a standard height of 30 feet

PE = Thornthwaite's precipitation-evaporation index
= 0.83 (sum of 12 monthly ratios of precipitation to actual evapotranspiration).

Monthly or seasonal climatic factors can be estimated from equation (2) by substituting the mean wind velocity of the period of interest for the mean annual wind velocity. The annual PE value is used for all calculations of C.

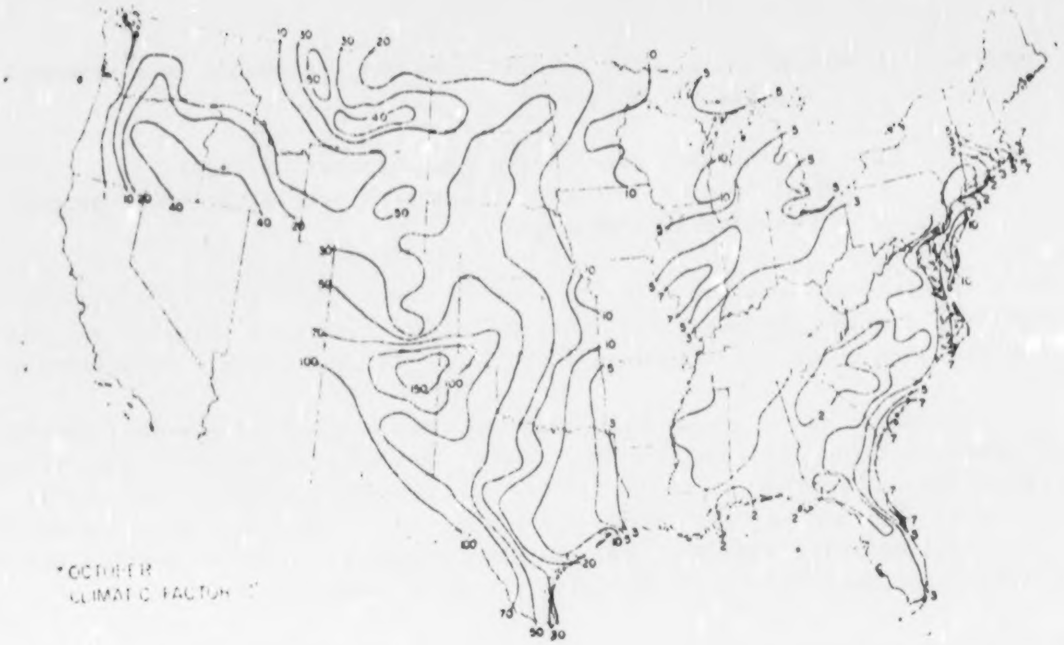
Climatic factors have been computed from Weather Bureau data for many locations throughout the country. Figure A-4 presents several maps showing some typical monthly climatic factors for the USA. C values for use in equation (1) may be taken from appropriate maps like these when preparing regional emission surveys. For emission estimates covering smaller areas, either equation (2) or the map may be used to obtain C.

Unsheltered Field Width Factor, L'

Soil erosion across a field is directly related to the unsheltered width along the prevailing wind direction. The rate of erosion is zero at the windward edge of the field and increases approximately proportionately with distance downwind until, if the field is large enough, a maximum rate of soil movement is reached.

Correlation between the width of a field and its rate of erosion is also affected by the soil erodibility of its surface: the more erodible the surface, the shorter the distance in which maximum soil movement is reached. This relationship between the unsheltered width of a field (L), its surface erodibility (IK), and its relative rate of soil erosion (L') is shown graphically in Figure A-5. If the curves of Figure A-5 are used to obtain the L' factor for the windblown dust equation, values for the variables I and K must already be known and an appropriate value for L must be determined.

L is calculated as the distance across the field in the prevailing wind direction minus the distance from the windward edge of the field that is protected from wind erosion by a barrier. The distance protected by a barrier is equal to 10 times the height of the barrier, or 10 H. For example, a row of 30-ft high trees along the windward side of a field reduces the effective width of the field by 10 x 30 or 300 ft. If the prevailing wind direction differs significantly (more than 25 degrees) from perpendicularity with the field, L should be increased to account for this additional distance of exposure to the wind. The distance across the field,


OCTOBER
CLIMATIC FACTOR

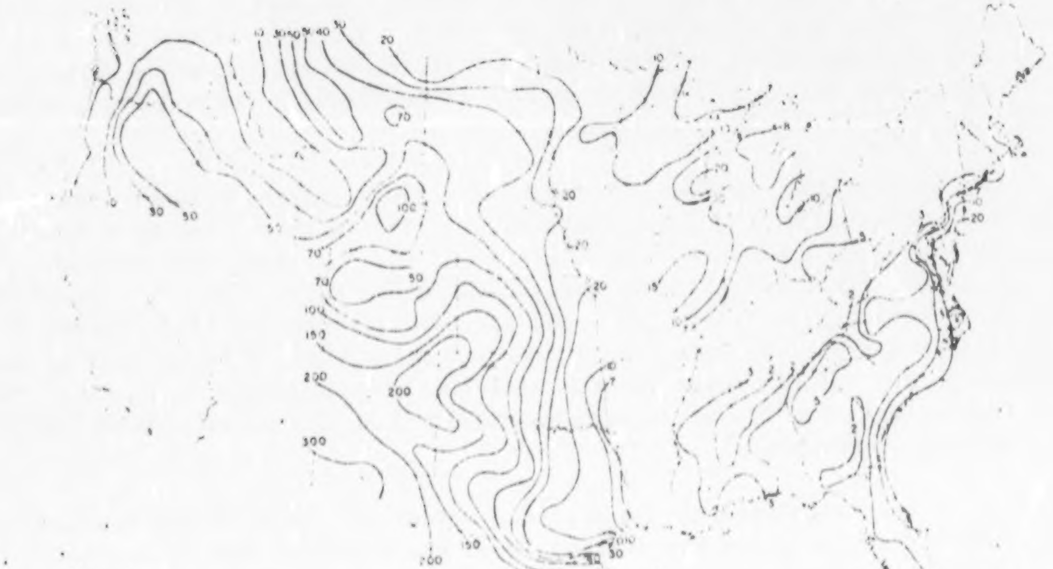

MARCH
CLIMATIC FACTOR

Figure A-4. Typical monthly climatic factors for the U.S.

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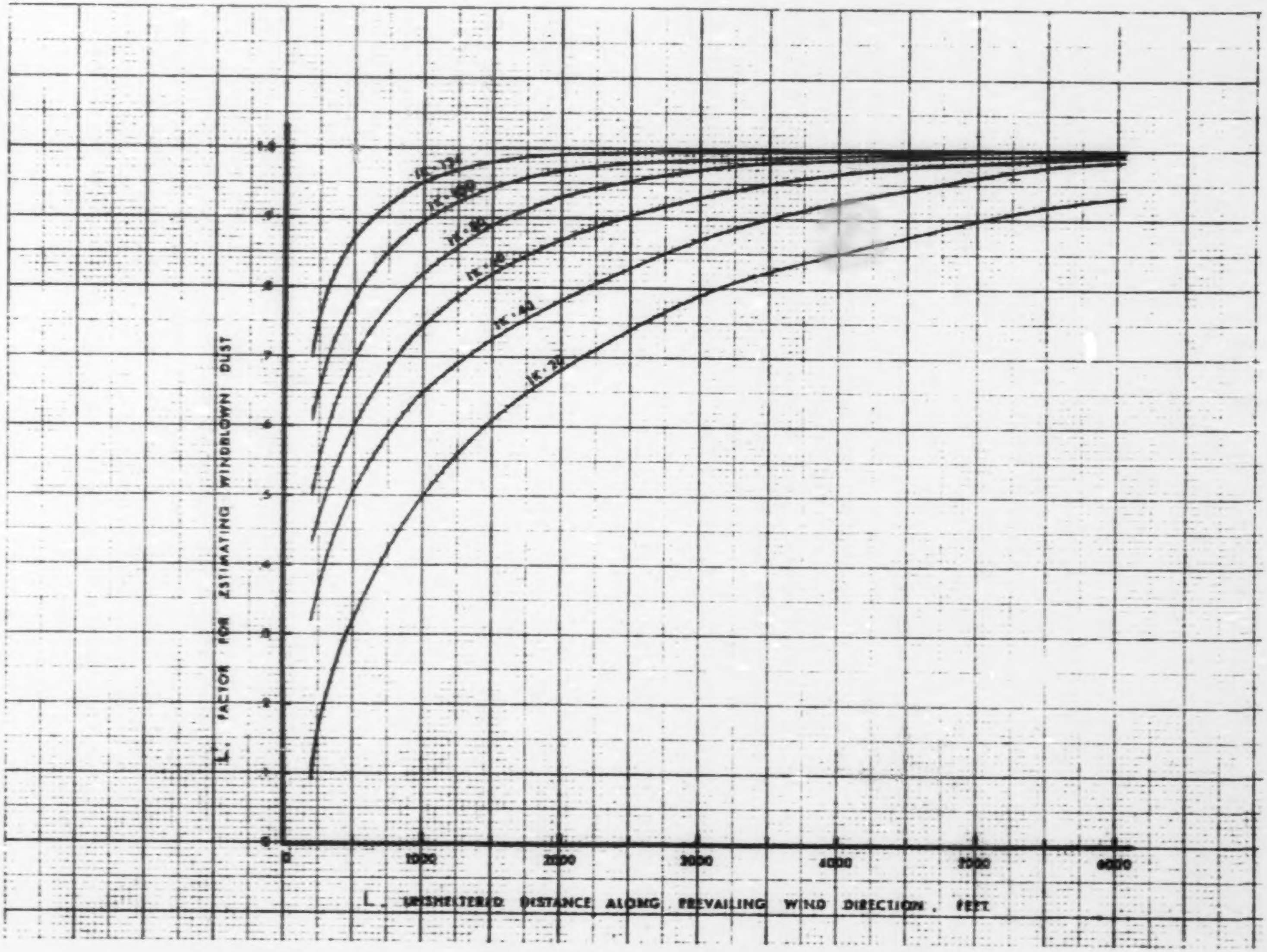

Figure A-5. Effect of field length on relative emission rate.

L is equal to the field width divided by the cosine of the angle between the prevailing wind direction and the perpendicular to the field:

$$L = \frac{w}{\cos A}$$

For multiple fields or regional surveys, measurement and calculation of L values become unwieldy. In region-wide emission estimates, average field widths should be used. Field width is generally a function of the crop being grown, topography of the area, and the amount of trees and other natural vegetation in or adjacent to the farming areas that would shelter fields from erosive winds. Since the windblown dust calculations are already split into individual crop type to accurately consider variations in K by crop, average L values have also been developed by crop; they are presented in Table A-2. These values are representative of field sizes in relatively flat terrain devoid of tall natural vegetation, such as found in large areas of the Great Plains. The L values in Table A-2 should be divided by 2 in areas with moderately uneven terrain and by 3 in hilly areas. Additionally, the average field width factors should be divided by 2 to account for wooded areas and fence thickets interspersed with farmland.

Vegetative Cover Factor, V'

Vegetative cover on agricultural fields during periods other than the primary crop season greatly reduces wind erosion of the soil. This cover most commonly is crop residue, either standing stubble or mulched into the soil. The effect of various amounts of residue, V, in reducing erosion is shown quantitatively in Figure A-6, where IKCL' is the potential annual soil loss (in tons/acre/year) from a bare field, and V' is the fractional amount of this potential loss which results when the field has a vegetative cover of V, in lb. of air-dried residue/acre. Obviously, the other four variables in equation (1)--I, K, C, and L'--must be known before V' can be determined from Figure A-6.

The amount of vegetative cover on a single field can be ascertained by collecting and weighing clean residue from a representative plot or by visual comparison with calibrated photographs. The weight obtained by either measuring method must then be converted to an equivalent weight of flat small grain stubble before entering Figure A-6, since different crop residues vary in their ability to reduce wind erosion. Detailed descriptions of the measuring methods or conversion procedures are too complex for this presentation. Interested readers are referred to a USDA publication for these descriptions.[A3]

The residue left on a field when using good soil conservation practices is closely related to the type of crop. Table A-2 presents representative

THE HOLY YEAR OF
1975

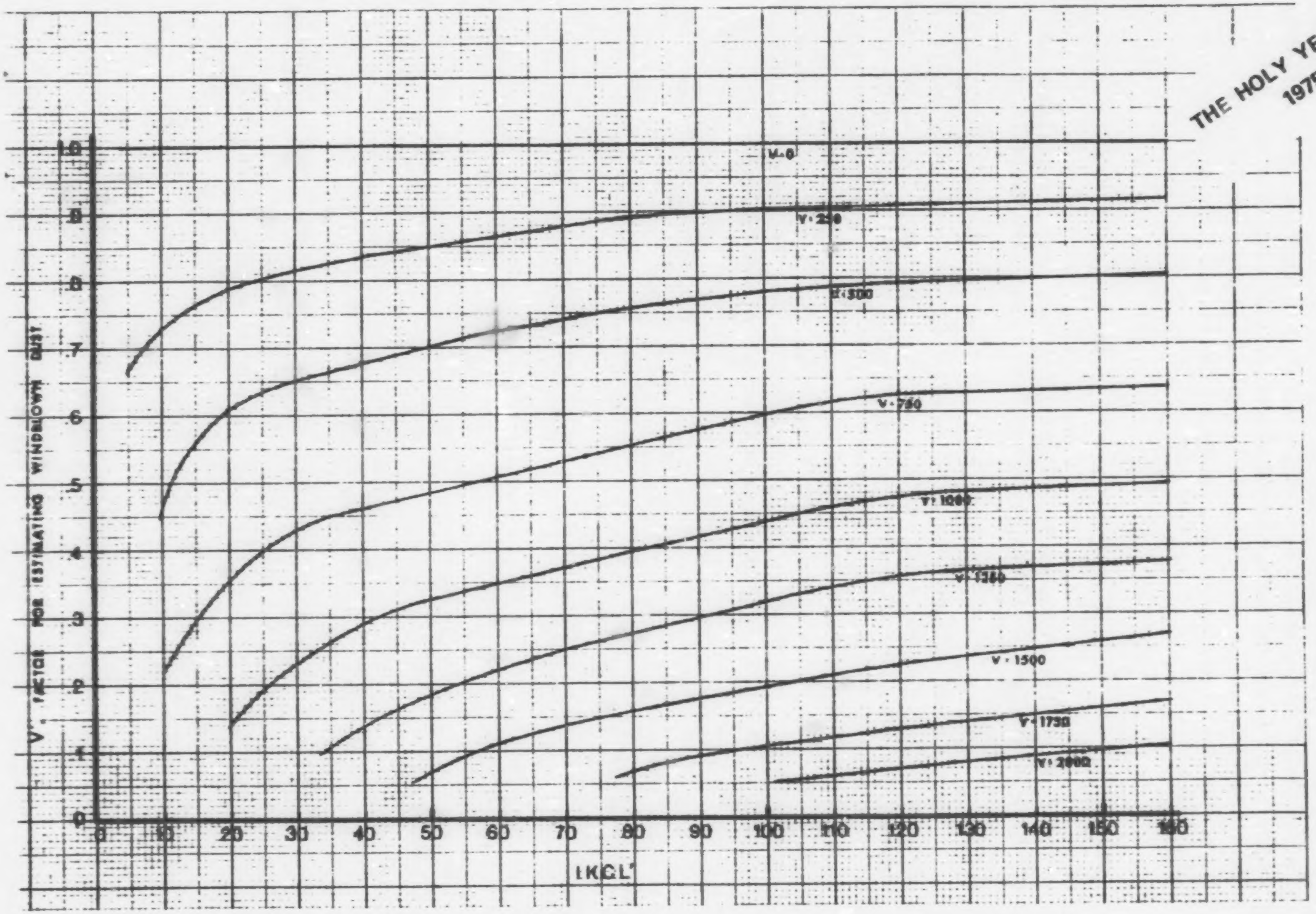

Figure A-6. Effect of vegetative cover on relative emission rate.

values of V for common field crops when stubble or mulch is left after the crop. These values should be used in calculating windblown dust emissions unless a knowledge of local farming practices indicates that some increase or decrease is warranted. Note that three of the five variables in the windblown dust equation are determined as functions of the crop grown on the field.

SUMMARY

The estimated emissions in tons/acre/year may now be calculated for each field or group of fields as the product of the five variables times the constant "a".

For regional emission estimates, the acreage in agriculture should be determined for each jurisdiction (e.g., county) by crop. "I" and "C" values can be determined for individual jurisdiction, with the remaining three variables being quantified as functions of crop type. The emission calculations are best performed in a tabular format such as the one shown in Table A-3. The calculated emissions from each crop are summed to get agricultural wind erosion emissions by jurisdiction and these are totaled to get emissions for this source category for the entire region.

Table A-3. CALCULATION SHEET FOR ESTIMATION OF DUST FROM WIND EROSION

Jurisdiction (County)	I, Based on Soil Type	C, Climatic Factor	Crop	Acres	K, Surface Roughness	L, Field Length	V, Veget. Cover	L', Length Factor	V', Veget. Factor	E, = aIKC-L'V'	Total Emissions By Crop
			Alfalfa								
			Barley								
			Beans								
			Corn								
			Cotton								
			Potatoes								
			Sorghum								
			Soybeans								
			Sugar Beets								
			Vegets.								
			Wheat								
			Etc.								
										Total	
			(List of Crops Grown in Jurisdiction)								
										Total	

APPROPRIATE USAGE OF RESULTS

Inherent variabilities in the many parameters used in the windblown dust equation cause the results to be less accurate than emission estimates for most other sources. However, the rough estimates provided by the proposed procedure are better than not considering this source at all in particulate emission inventory work. Inclusion of this source category, possibly with some qualifying statement as to its relative accuracy, gives an indication of its contribution to regional air quality.

The estimation procedure is not intended for use in predicting emissions for short time periods, nor can it be used in determining emission rates for enforcement purposes.

REFERENCES

A1. PEDCo-Environmental Specialists, Inc., "Investigation of Fugitive Dust--Sources, Emissions and Control," Environmental Protection Agency Contract No. 68-02-0044, Task Order No. 9, May 1973.

A2. Hagen, L. J., and N. P. Woodruff, "Particulate Loads caused by Wind Erosion in the Great Plains," presentation at the 66th Annual Meeting of Air Pollution Control Association, June 1973.

A3. Craig, D. G., and J. W. Turelle, "Guide for Wind Erosion Control on Cropland in the Great Plains States," USDA Soil Conservation Service (1964).

APPENDIX B

DISPERSION CALCULATIONS FOR CONSTRUCTION EMISSIONS

Table B-1 below presents the concentrations recorded during periods of southerly, southwesterly and westerly winds at the Paradise Valley construction site.

Table B-1. MEASURED CONCENTRATIONS DURING S, SW AND W WINDS ($\mu g/m^3$)

Station Date	Station C-13	Station C-14	Station C-15	Station C-11 (bkgnd)	Wind	
					Speed	Dir.
8-31-72	-	324	363	347	9 mph	SW
9-6-72	461	280	169	152	3	
9-12-72	487	368	365	152	3	
Average	474	324	299	217	5	
9-4-72	353	370	328	203	6	S
9-14-72	389	258	292	212	7	
Average	371	314	310	208	6.5	
9-20-72	212	251	141	95	2	W
9-28-72	375	336	240	163	2	
9-30-72	-	312	415	185	5	
10-6-72	-	70	-	170	2	
Average	294	241	299	153	2.75	

FOR SOUTHWESTERLY WIND

I. (a) Average concentration at downwind stations:

Station	C-13	474 $\mu g/m^3$
	C-14	324
	C-15	299
Average		1097/3 = 366 $\mu g/m^3$

(b) Average concentration at background station:
Station C-11 217 $\mu g/m^3$
Contribution from the construction site =
366 - 217 = 149 $\mu g/m^3$

(c) $Q = 2.78\ \chi u \sigma_y\ \sigma_z$

where Q = source strength (grams per second)
χ = concentration (grams per cubic meter)
u = wind speed (meters per second)
σ_y = horizontal dispersion coefficient (meters)
σ_z = vertical dispersion coefficient (meters).

[NOTE: The factor of 2.78 was derived from Table 5-1, page 38 of "Workbook of Atmospheric Dispersion Estimates," PHS Publication No. 999-AP-26. Ratio of calculated 24-hr concentration to 3-min concentration = 1.00/0.36 = 2.78.]

u = wind speed = 5 mph = 2.23 m/sec

For wind speed of 2.23 m/sec and assuming moderate to strong solar radiation based on Table 3-1 of above reference, stability class = B.

Using the method of approximation outlined for area sources in the above reference (pages 39 and 40), σ_y and σ_z values were obtained from appropriate figures for $X_1 = X + X_{yo}$
where X is the distance of sampler from the source,
X_{yo} is virtual distance corresponding to
$\sigma_{yo} = S/4.3$ and
S is the length of a side of the area source.

Distance from center of construction area to sampler locations (measured from the map):

C-13	1,000 ft
C-14	2,400 ft
C-15	3,350 ft

Average Distance = $X = 6750/3 = 2250$ ft $\approx$ 690 m
$\sigma_{yo} = S/4.3 = 650/4.3 = 150$ m
For $\sigma_{yo} = 150$ meters, $X_{yo} = 960$ m (from chart, stability class = B)
$X_1 = X + X_{yo} = 690 + 960 = 1{,}650$ m
For $X_1 = 1650$ meters, $\sigma_y = 250$ m
$\sigma_z = 190$ m
Substituting these values in the expression for $Q = 2.78 \chi u \sigma_y \sigma_z$, we get:

$Q = 2.78\ (0.000366 - 0.000217)\ (2.23)\ (250)\ (190)$
= 43.8 g/sec, or
= 1,525 tons/ year, or
= 1.41 tons/acre/month of active construction (based on 90 acres under active construction at this location)

[NOTE: Particulate concentration used was the difference between upwind and downwind sampling locations and is thought to represent only the contribution from the construction site.]

II. (a) Average concentration at the closest downwind station - station C-13 only = 474 $\mu g/m^3$

(b) Average concentration at background station - station C-11 = 217 $\mu g/m^3$

Contribution from the construction site = $474 - 217 = 257\ \mu g/m^3$

(c) $Q = 2.78 \chi u \sigma_y \sigma_z$
u = 5 mph = 2.23 m/sec
χ = 0.000257 g/sec
X = distance of sampler from center of construction area $\cong$ 1,000 ft or 305 m
$\sigma_{yo} = 650/4.3 = 150$ m
X_{yo} (from graph in the Reference, Stability Class = B) = 960 m
$X_1 = X + X_{yo} = 305 + 906 = 1{,}265$ m
σ_y = 190 m
σ_z = 140 m
$Q = (2.78)\ (0.000257)\ (2.23)\ (190)\ (140)$
= 42.5 g/sec, or
= 1,480 tons/year, or
= 1.37 tons/acre/month of active construction

Performing these calculations for the other two wind directions of interest, namely, southerly and westerly winds, the source strength values shown in Table 36 (Chapter 7) were obtained.

APPENDIX C

PHOTOGRAPHS OF FIELD TESTING

This appendix presents representative photographs of field equipment used in testing dust emissions from unpaved roads and agricultural tilling. Figure C-1 shows the dust sampling equipment used at gravel road Site R2, and Figure C-2 shows the tillage equipment used at the agricultural sites in Wallace County, Kansas.